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HEAT AND MOISTURE LOADS IN PULLET BARNS

by

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Abstract

Reliable data on heat and moisture loads and air quality parameters in replacement pullet units are necessary for the design of effective, energy-efficient, environmental control systems appropiate to Canadian conditions. This information also must cover variations, if any, resulting from housing and management practices. The primary objectives of this study were to establish heat and moisture loads and their variability under commercial conditions, establish production rates and concentrations of air contaminants, and to determine the possible effect of management practices on air quality parameters. These parameters consisted of carbon dioxide, ammonia, hydrogen sulphide, and dust. A secondary objective was to report on findings arising directly or indirectly from this study that would be useful for extension purposes in replacement pullet units.

Two commercial poultry rearing barns, located near Edmonton, Alberta, were monitored for 24-hour periods during each month of the 18 to 20-week rearing cycle over the winter period. One barn was representative of the cage rearing system and the other of on-floor rearing. A data recording system developed by the Department of Agricultural Engineering, University of Alberta, was used to collect the necessary data required to carry out a complete heat and moisture balance on each barn and to monitor the air

quality of the replacement pullet environment.

The heat losses, through conduction and ventilation, and the supplemental heat gains were calculated using the dry-bulb temperatures and dewpoints of the incoming, outgoing, and ambient air, together with exhaust air flows and hot-water flow. The heat and moisture loads, in turn, were derived from the heat and moisture gains and losses from the buildings. The unknown total heat and moisture loads of the birds were derived by balancing the measured physical heat and moisture components of the barn.

The total heat production of the White Leghorn type pullets ranged from 2.3 to 30.5 kJ/(h.bird), while the moisture produced from the barn ranged from 0.7 to 4.1 g/(h.bird), over the rearing cycle. Over two thirds of the total heat removed in the exhaust air was in sensible form. The conversion of sensible to latent heat in evaporation of moisture ranged from 3 to 50 percent and from 12 to 33 percent of bird sensible heat production over the rearing cycle for the on-floor and cage units, respectively.

Ranges of background concentrations for carbon dioxide, ammonia, hydrogen sulfide, and dust were established. Ammonia and dust concentrations in the on-floor unit were considered to be potentially hazardous to both pullets and operators. The overall air quality in the cage unit remained fairly constant and was superior to that in the on-floor operation. There was a marked decrease over

time in air quality in the on-floor units. Regression equations were developed to predict total heat, moisture, and carbon dioxide production rates of the pullets as a function of their age. Management practices appear to have a very significant affect on air quality parameters.

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1. INTRODUCTION

Control of the barn environment is an essential component of a successful poultry operation under the weather conditions found in Alberta. To achieve optimal growth and performance of the birds requires consideration, not only of the thermal parameters that define their environment, but also consideration of the non-thermal or air quality parameters such as gaseous contaminants and aerosolized particles or dust. In addition, very little is known concerning the effects of air contaminants on the health and safety of animals and humans operating within these confinement units.

A continuous supply of uncontaminated air is a requirement for health and optimum performance of farm animals. Air contaminants are produced by the animal and by factors within its immediate environment. Animals produce moisture and gases in exhaled air, dust in the form of tissue debris, and micro-organisms which possibly may be pathological. Air contaminants also include moisture and gases resulting from the evaporation and breakdown of faeces and urine, dust from feed or bedding, and micro-organisms which may multiply at a fast rate in an environment modified by the presence of animals.

The production of these air contaminants does not present any problems to animals in their natural habitat. Natural air movement serves to dilute air contaminants and to transport them away from the immediate vicinity of the animal. Alternatively, if the animal senses an increase in the pollution of its micro-environment, it has the option to move from the contaminated zone. Under controlled atmosphere conditions, however, the situation is quite different. Many of the advantages of maintaining a thermal environment within the optimum range have been lost, in some cases, due to the presence of high concentrations of air pollutants. Under these enclosed conditions, animals usually do not have the option of moving away from a polluted micro-environment.

A building heat balance is of fundamental importance in the design of environmental control systems for confinement poultry facilities. The critical elements of this balance are the conductive heat losses through the various building components, the heat losses due to ventilation and the heat gains from the birds as a result of their metabolic activity. To achieve this balance in cold weather, supplemental heat input may be necessary to make up any deficit and to maintain a desirable ambient temperature within the barn.

The accuracy of the building heat balance is contingent upon the reliability of input data. In this regard, conductive heat losses through the building shell can be calculated from readily-available information with acceptable accuracy, while supplemental heat is the variable that can be controlled most easily. Ventilation heat losses, however, are a direct function of the ventilation rate, as well as inside-to-outside differences in temperature and absolute humidity. In turn, ventilation rate in cold conditions must be adequate to control moisture within the building, the primary source of this moisture being the birds. A secondary source of moisture is evaporation from wet surfaces, such as waterers and droppings, within the building. This evaporation involves a conversion of sensible heat released by the birds and supplemental heating to latent heat. Therefore, the key element of the heat balance is the birds' heat output or, more specifically, their sensible and latent heat output.

During winter, large quantities of outside air are not required to move through the barn. The ambient air is cooled by the sensible heat losses through the shell of the barn. The animals themselves generate sensible heat to warm the barn, in addition to latent heat. Evaporation also occurs, for example, from manure pits, floors, and waterers, and latent heat is released into the air. Cold outside air, when warmed to room temperature, can pick up large amounts of moisture as latent heat. The relative humidity is controlled at the optimum level by replacing small amounts of the humid inside air with dry outside air. The sensible heat produced by the birds is not always sufficient both to warm the cold air coming into the barn and to compensate for the building heat loss, with the result that supplemental heating systems are installed to overcome this heat deficit and to ensure a balance of ambient conditions.

The presence of atmospheric gaseous contaminants in confinement units create a dilemma with regard to the design of a sound ventilation system. Gases found in animal buildings are usually the by-products of respiration, fermentation and biological degradation of organic compounds. Carbon dioxide (CO_2) and, in the case of ruminants, methane (CH_4) are the primary constituents of the air exhaled by animals. Along with these gases, ammonia (NH_3) and hydrogen sulphide (H_2S) also may be released by biological decomposition of stored animal wastes. Data relating to the quantities of gases produced within a building under different manure handling systems for various classes of livestock and poultry under different feeding regimes are virtually non-existent. Again, information on threshold limits of the gases involved, when present singly or synergistically, are very sparse. Ventilation systems were designed to maintain a comfortable thermal environment and an acceptable CO_2 and NH_3 concentration using the concept that the heavier gases accumulate near floor level and the lighter gases move upward from their point of generation. Recently, this theory has been discounted in that little stratification was found in a well ventilated facility since temperature gradients and air movement were found to be responsible for diffusing the gases fairly evenly throughout the room atmosphere.

2. LITERATURE REVIEW

2.1 Environmental Demands

2.1.1 Historical Perspective

The evolution of birds is uncertain but Huxley (1868) and Ostrom (1976), as cited by Graves (1982), claim that fossil chickens evolved from warm-blooded dinosaurs while another school of thought suggests that they evolved from cold blooded reptiles (Romer, 1966). However, Hutt (1949), as cited by Graves (1982), concluded that the domestic chicken evolved from the jungle fowl of Southeast Asia. Man has assisted in the domestication of the chicken by providing protection from the elements by environmental modification and control.

Traditionally, as discussed by Byerly (1960), poultry and eggs were the main sources of fresh meat for the farm family. The poultry industry became highly intensive in the 1940s due mainly to the higher food costs and greater food losses incurred under external environmental conditions. Arguments developed for better environmental control in poultry houses were outlined by Sainsbury (1980). He stated that productivity was increased by the use of a controlled lighting schedule in windowless houses.

Farrell (1974) commented that the total heat production of poultry was mainly determined by either the direct measurement of total heat emission from the bird or by its estimation from an analysis of the evolved gases from the birds metabolism. This bird total heat production was used to estimate the feed energy requirements of the bird, particularly that required for maintenance and growth (Mitchell and Haines, 1927; Deighton and Hutchinson, 1940b; Shannon and Brown, 1969a; Burlacu et al., 1970a,b). Factors such as the energy cost of maintenance and production (Waring and Brown, 1965, 1967; Grimbergen, 1970; van Es et al., 1970; Burlacu and Baltac, 1971), tissue synthesis (Burlacu et al., 1970b; Peterson, 1970; Shannon and Brown, 1970), effects of temperature (Romijn and Lokhorst, 1966; Shannon and Brown, 1969a,b; O'Neill et al., 1970), disease (Sykes, 1970; Farrell and Walker, 1973), nutrient imbalance (Baldini, 1961), deficiencies (Kleiber, 1945; Guo and Summers, 1970), and other conditions that may change the energy expenditure of the bird, can be assessed.

Total heat and moisture production of animals has been measured traditionally by either direct or indirect calorimetry. Pullar (1969) described the methods used to measure the heat emitted by domestic animals using direct calorimetry and also an historical account of the development of this system. The total heat emitted by animals is composed of sensible heat loss which, may be partitioned into convection, radiation, and conduction, and latent or evaporative heat loss of moisture by respiratory and cutaneous routes. Heat loss by an animal in vaporizing moisture varies depending on body surface and environmental temperature (Blaxter, 1967).

Direct calorimetry is based on the principle that the total heat produced by the animal is used to increase the temperature of a suitable medium such as ice or water while preventing heat exchange with the environment through the use of an adiabatic system (Pullar, 1969). Evaporative heat loss is calculated by weighing the water, produced by the animal, which is absorbed in a chemical drying agent. Another type of direct calorimeter is the "compensatory" calorimeter which consists of two chambers. The total heat production of the bird in one chamber is kept in equilibrium by a controlled heat source in the other chamber. Deighton (1939) used this principle to calculate the total heat produced by the bird.

More recently the direct measurement of total heat loss has relied on the gradient layer principle. This enabled the direct measurement of the instantaneous flow of both sensible and evaporative heat loss. Several thousand pairs of thermojunctions in gradient layers located between the inner and outer wall of the chamber measure the heat flowing out. The temperature of the outer wall is held constant and heat passing through this wall is transferred to a water jacket. Moisture production is determined by passing chamber air through heat exchangers (Pullar, 1969). However, evaporative heat loss includes the moisture contained in the excreta and, consequently, these values may be overestimated by 10 percent (Pullar, 1969) and sensible heat loss underestimated by the same amount.

In more recent years, direct calorimeters have been utilized on a smaller scale due to cost and technical difficulties. Direct calorimeters suitable for the measurement of total heat emission by fowl have been described by Benedict et al. (1932), cited by Balnave (1974), Barott (1937), Deighton (1939), Pullar (1957) and Roller and Dale (1963). Indirect calorimetry, as described by Flatt (1969), measures the variations in the chemical composition of the nutrients after undergoing catabolism or storage in the animal's body. A major advantage of the direct system is that, because of its rapid response time, fluctuations in heat loss, often due to activity of the birds (Deighton, 1939; Deighton and Hutchinson, 1940a) can be determined.

Respiratory quotient (RQ) is defined, according to Farrell (1974), as the ratio of the volume of CO_2 produced to the volume of oxygen (O_2) consumed. The production of heat is related to the amount of CO_2 and water (H_2O) oxidised in the process of feed digestion. Most feedingstuffs, usually composed of fat, protein, and carbohydrate, have different carbon (C), O_2, and hydrogen (H_2) contents. Therefore, the RQ may be used to give an indication of the components used to provide energy, as described by Richardson, 1929, cited by Farrell (1974), and Kleiber (1975). Heat production can be calculated from the thermal equivalents of O_2 or CO_2 at a particular RQ from tables of published values (Brody, 1945).

2.1.2 Thermal Environment

Starr (1981) observed that productivity and reproductive efficiency can be increased by controlling the range of an animal's thermal environment. Esmay (1979) defined environment as the summation of each factor that influences animals' productivity. These factors further were sectioned into physical, social and thermal environment. Thompson (1974) considered the environment as comprising a contact segment, consisting of the housing and machinery with which the animal interacts, and a non-contact segment, consisting of lighting and air conditions and contaminants. In fact, the differences implied by different users are often merely differences of level in which a poultry house is situated within its macro-environment and has a meso-environment within it.

In relation to the thermal environment, animals necessarily generate metabolic heat and this heat has to be dissipated to the environment by the processes of conduction, convection, radiation, and evaporation. The net effect of these processes is important to heat dissipation, although one process may be dominant. Esmay (1979) suggested that the thermal environment within a confinement unit may be analyzed on the basis of the First Law of Thermodynamics, that is, conservation of energy within the system.

Environmental conditions, therefore, will be determined by the climatic state at which the building energy balance is in equilibrium. This concept assumes that steady-state conditions exist.

Starr (1981) observed that over a limited range of environments, commonly denoted by the thermoneutral zone, a ready balance may be achieved between the animal's heat production and the environmental demand; within this zone the animal is not stressed in achieving a balance. Smith (1972) defined environmental demand as the total heat flow rate from a source to the environment. Outside this thermoneutral zone, the animal is stressed by environmental and pathological factors and, subsequently, production is decreased. Smith (1972) introduced the additional concept of environmental quality, meaning the degree of freedom from contaminants and pollution.

2.1.3 Air Exchange

Under steady-state conditions, energy is conserved within livestock buildings. Thermal energy is produced by the animals, by lighting and mechanical equipment, and by supplemental heating systems. In most instances, supplemental heat only is required to maintain an energy balance. Sensible heat is used to evaporate liquid water from wet surfaces within the barn, and, in doing so, is converted to latent heat, as observed by Dick and Loader (1960). Most of the sensible heat generated within the building is exhausted by the fans, with small quantities lost through the structure, by conduction, and through evaporation of moisture from wet surfaces. ASHRAE (1978) suggested that moisture transfer through the structural components is negligible and could be ignored. Consequently, all the latent heat is lost through the fans.

Traditionally, in total confinement animal housing, the control of moisture as water vapour in the atmosphere is a prime function of ventilation under cold weather conditions. Animals lose moisture by excretion in urine and faeces and by evaporation from skin and lungs. The amount of drying achieved within poultry units using ventilation systems alone is variable (Longhouse et al., 1960). Where birds are kept on litter, the ventilation should be capable of keeping litter in a "dry" condition (30-35 percent moisture) and the rates of ventilation should remove all moisture produced within the barn. The production of water vapour within such a building is not only the result of moisture evaporation from the animals themselves but also arises from evaporation of moisture from various sources including floor surfaces, waterers, and the animal wastes.

A measure of water vapour production within the building is the latent heat loss from the building. This heat loss in the form of water vapour may vary considerably, as outlined by Dick and Loader (1960), depending upon management practices, building design, and effectiveness of the ventilation system. Longhouse et al. (1960) claimed that the moisture released in the poultry house depends on the size and breed of birds, environmental conditions, and density of the bird population.

Smith (1975) suggested that the purpose of a ventilation system is to provide the optimum conditions for the livestock by controlling the thermal environment. To achieve this, the two basic functions of a ventilation system are to provide effective control over the ventilation rate and efficient control over the airflow pattern within the ventilated structure. These should be attained simultaneously. Therefore, careful attention should be given to the design and siting of the ventilation equipment. In addition, a ventilation system should control the air quality within the confinement unit.

During the cool part of the year, a variety of management and climatic circumstances could lead to the condensation of water vapour on the surfaces of the interior linings and on or within insulation materials and framing timbers. Condensation will occur if the temperature of a surface falls below the dewpoint of the air in contact with the surface, as explained by Smith (1975). The problem of condensation in winter involves consideration of two basic environment control factors; the control of temperature and its retention through insulation and adjustment of ventilation rates, and the production of moisture and its rejection from a building. During winter when the moisture content of the air in a building is substantially greater than outdoor air, the gradient of water vapour pressure across the building structure at any point will act to force the vapour through the building materials and be released in the outside air. The materials used in building poultry houses vary in their ability to resist the passage of water vapour.

Solutions for determining the ventilation rate for any given set of conditions were given by Reece and Lott (1982). They claimed that the basis for ventilation rates within a confinement unit may be determined by balancing the ventilated moisture with either the bird sensible or latent heat output. The normal practice is to use the first solution during warm summer conditions and the second during cold, winter conditions.

Minimum air requirements for layers and broilers have been determined by Charles and Payne (1966a,b), in experiments using large numbers of birds, where performance was measured as well as air composition. The rates are system-dependent, since the limiting factor tends to be NH_3 and this is influenced by such factors as manure handling and litter condition. Minimum ventilation rates are defined by the minimum amounts of air needed to provide O_2, remove contaminants and excess moisture, and to support maximum levels of production. The choice of the correct minimum is critical in cold weather, because the lower the value used, the warmer the inside temperature obtainable without the use of supplemental heat.

Winter minimum ventilation rates for confinement housing normally are based on moisture control. This practice implies that air contaminants and odours within the barn also will be removed and controlled at acceptable concentrations. Unfortunately, quantitative information in this regard is sparse, although perhaps understandable in that large scale animal production is a comparatively recent development. However, air quality in poultry housing increasingly is suspected of playing a very significant role in bird health and performance (Reece et al., 1981; Nagaraja et al., 1983). In addition, attention recently has been focused on air quality in animal housing and its relationship to occupational health concerns for humans working in such facilities (Donham and Gustafson, 1981). Yet a further concern is the probability that air quality parameters may be associated with the quality of products produced within confinement units, particularly in the case of poultry operations (Curtis, 1981; Froning and Sackett, 1984). The practice of reducing minimum winter ventilation rates below normally recommended levels for reasons of feed economy or energy conservation may exacerbate potential problems associated with air quality.

2.1.4 Thermoregulation

Curtis (1981) outlined the main environmental factors which determine the loss of heat from a homeotherm as the temperature, humidity, ambient air velocity, and the distribution of radiant energy over the body surface. Mount (1979) applied the term homeotherm to an animal "that usually maintains a stable deep body temperature (core temperature) within relatively narrow limits although the environmental temperature may fluctuate and although the animal's activity may vary greatly".

Under cold conditions, the homeotherm's core temperature range shrinks and the limbs and peripheral tissues become colder (Mount,1979). Aschoff and Wever (1958), as cited by Mount (1979), observed that, under warm conditions, very large parts of the tissues of the limbs and the peripheral tissues of an animal's trunk have temperatures similar to that of the core. The essential feature of the homeotherm is that the core temperature is maintained around a level that is independent of environmental fluctuation.

Fluctuations of body temperature lead to physiological and behavioural responses. Scott et al. (1983) noted that behavioural responses may be regulated by the management system, that is, by controlling the temperature and air flow. Animals have different pathways for adapting a comfortable thermal environment, as outlined by Mount (1979), when under thermal stress. Mount (1979) claimed that,

> "Above the set-point temperature, heat dissipation is increased by sweating or panting, and heat conservation is decreased by peripheral vasodilatation, which is the dilation of skin blood vessels under warm conditions. However, when the core temperature falls below the set-point temperature, heat dissipation is reduced, heat

> conservation is increased by piloerection (the fluffing up of the coat) and by peripheral vasoconstriction (the closure of skin blood vessels that occurs under cool conditions), and total heat production is increased (by shivering or non-shivering thermogenesis). The range of environmental temperature in which the animal's metabolic rate is at a minimum, constant and independent of the environmental temperatures is known classically as the zone of thermal neutrality or thermoneutral zone."

There is extensive literature relating to the subject of thermal regulation, including many reviews (Benzinger, 1971; Bianca, 1968; Bligh, 1973; Mitchell et al., 1972).

2.1.5 Energy Transfer

In animals, the core temperature is maintained by balancing the total heat production against the total heat loss. The total heat loss is influenced by environmental conditions and the adaptive ability of the animal. The animal may adapt itself physiologically, morphologically, or behaviourally as shown by Mount (1979). Under cold conditions, the total heat produced is conserved by peripheral vasoconstriction and pilo-erection which increases the peripheral insulation. Heat is dissipated from the surface, under warm conditions, by peripheral vasodilatation. This process is accomplished by the blood-flow bypassing the subcutaneous fat layer and, thus, minimizing the effect of fat insulation. Mount (1979) recognized that for heat conservation the animal's behavioural responses lead it, "to adopt a compact posture, under cold conditions, with the minimum exposure of body surface to the environment" and for heat dissipation, "to extend their posture, under warm conditions, with limbs spread out, coupled with peripheral vasodilatation".

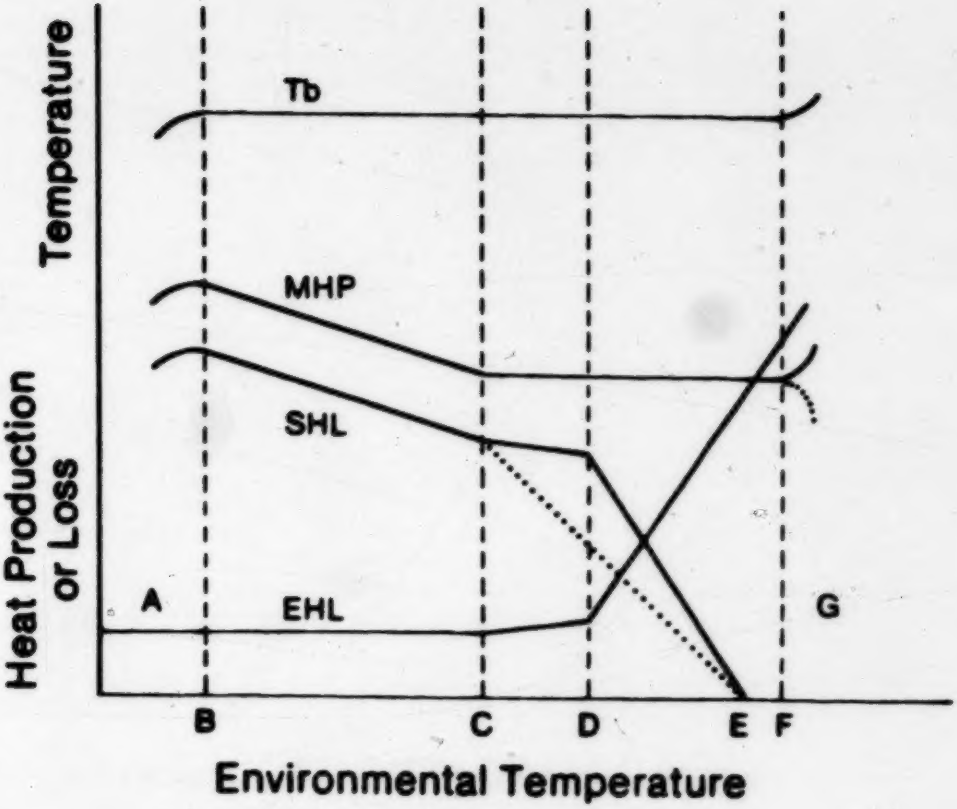
Mount (1979) outlined the processes involved in the heat exchange between the animal and its environment. This author equated the total heat transfer with the summation of its individual components, namely, evaporation, radiation, convection, and conduction. The resultant value may be a net loss or gain. He further apportioned the modes of heat transfer to evaporative and non-evaporative. Alternatively, these modes may be named as latent and sensible heat transfer, respectively. The sensible heat exchange, which is dominant under cold conditions, depends on a temperature differential between the animal and its environment. Mount (1979) stated that latent heat transfer depended upon the water vapour pressure differential between the animal and its environment and considered this transfer to be a net heat loss.

2.1.6 Energy Metabolism

Scott et al. (1983) defined net energy as, "the difference between energy intake and energy losses". The animal utilizes this net energy for production, reproduction and work. Under cold conditions, researchers reported an increase in gross energy intake (Baile and Forbes, 1974; van Kampen, 1974; Baumgardt et al., 1976) and also in fecal and urinary wastes of ruminants (Young, 1979), while a decrease was evident during warm conditions. The metabolizable energy (ME) was defined by Miller (1974) as the gross energy or heat of combustion of the feed intake minus the gross energies of the faeces and urine. Therefore, ME changes with temperature and represents the total feed energy intake that the animal can utilize for protein and fat deposition. The relationship between animal heat loss and temperature has been related graphically (Kleiber, 1961) and mathematically (Teter and DeShazer, 1976).

Direct calorimeters, as noted by Scott et al. (1983), measure heat loss and not metabolic heat production (MHP). However, total heat loss (THL) only is equivalent to MHP when the animal's core temperature is in the thermoneutral range, a case which was applicable to most of the reported studies. Metabolic heat is produced as a result of chemical energy in the food being converted into heat energy.

The animal's thermal energy balance is given by the schematic diagram in Figure 2.1. This diagram was developed by Mount (1973), but is very similar to a figure presented by Esmay (1979). Figure 2.1 is a highly simplified diagram, as defined by Scott et al. (1983), to illustrate the relationships between MHP, sensible heat loss (SHL), evaporative heat loss (EHL) and deep-body temperature (Tb) as a function of environmental temperature. Mount (1973)



Tb = Deep-body Temperature
MHP = Metabolic Heat Production
SHL = Sensible Heat Loss
EHL = Evaporative Heat Loss

Figure 2.1. Thermal zones of mammals

described environmental temperature as the state in which the air temperature is equal to the mean radiant temperature and is under the influence of free convection at a relative humidity of 50 percent.

Actual values in Figure 2.1 and the relationship between the curves will depend on the species of animal as well as factors of nutrition, age, acclimation, behaviour, thermal insulation, and management systems. In this figure, zone BF is the zone of homeothermy. Heat production increases when the plane of nutrition increases. Temperatures B and F correspond to the incipient points of hypothermia and hyperthermia, respectively. Temperature C is the lower critical temperature, that is, the point at which MHP increases with decreasing ambient temperatures. Temperature D is the level where an increase in ambient temperature is accompanied by a sharp increase in EHL. Temperature E, where the sensible heat loss reaches zero, is the point where the environmental temperature equals body temperature (McLean, 1974). The branched line for metabolic heat production in zone G indicates both the increased energy expenditure of panting and exertion and decreased feed intake energy resulting in reduced production. The slope of the line at this point remains unclear as not enough experimental proof, under different conditions, has been obtained. The slope of the MHP line between B and C is a function of thermal insulation, that is, the greater the insulation, the less steep the slope.

The optimum environmental temperature for poultry can be determined by the thermoneutral zone, which is defined by Sturkie (1965) as the environmental temperature range within which fluctuations in bird heat production rates are minimal. This range would correspond to zone CF in Figure 2.1. The thermoneutral zone for the mature chicken, according to Sturkie (1965), ranges from 18 to 24 °C. Barott and Pringle (1951) reported that the thermoneutral zone for the hen was from 22.8°C to 27.7°C; Randall (1943) noted a range of from 19°C to 29°C. Barott and Pringle (1947; 1949; 1950) also found that the optimum temperature for chickens started at 34.4 °C at 1 day and decreased about 0.5 °C per day to 18.9 °C at 32 days of age.

2.2 Energy Expenditure of Poultry

The expenditure of energy in poultry is influenced by biological and other factors, such as age, acclimatization to temperature, activity, feather insulation, and breed effects. This energy expenditure is best studied with reference to basal metabolism. Balnave (1974) proposed that the basal metabolism represent the minimum energy required to maintain life. However, this value is extremely difficult to measure in birds under normal conditions and, consequently, the starving heat production usually is used as a reference.

2.2.1 Adaptation to Thermal Environment

Van Kampen (1981) sectioned the responses of birds to climatic changes into three stages: neuronal, hormonal and morphological. Harrison and Biellier (1969) found that birds acclimatized from 35 to 5°C showed an increase in metabolic rate and stated that both neuronal and hormonal responses were exhibited. In the mature fowl, Dukes (1947) and King and Farner (1961) reported that the starving metabolic rate is constant over an environmental temperature range of 8 to 12°C. Shannon and Brown (1969a), by measurement of starving metabolic rate, have shown that domestic fowl require time to acclimatize to an increase in environmental temperature from 22°C to 28°C.

The bird adapts biologically to changes in temperature by altering the pathway of heat dissipation from the body. Van Kampen and Romijn (1970) established the relative importance of these pathways from the body of mature hens. Below 15 °C, most heat was dissipated by radiative, conductive, and convective means from the body surface while evaporative heat loss was least. Evaporative heat loss increased when temperatures reached above 30 °C while there was a large reduction in heat loss from the body surface.

2.2.2 Daily Fluctuations

Mitchell et al. (1927) noted that the bird's metabolic rate fluctuated throughout the day. This, subsequently, was confirmed by Benedict et al. (1932), as cited by Balnave (1974), Barott et al. (1938), Deighton and Hutchinson (1940a,b), Barott and Pringle (1946) and Hohls (1954), as cited by Balnave (1974). More recent reports (Tasaki and Sakurai, 1964; Waring and Brown, 1965; Tasaki and Sasa, 1970) suggested that the bird's metabolism is maximal in the morning period (08.00 h to 12.00 h) and minimal at nighttime (20.00 h to 24.00 h). Hohls (1954), cited by Balnave (1974), has noted that daily variations in the heat production of the fed chicken can be reduced substantially if food is consumed between 15.00 h and 17.00 h rather than between 08.00 h and 10.00 h.

2.2.3 Feed

The Agricultural Research Council (1974) indicated that the ME requirements of laying hens for particular rates of production depended on whether they were derived from feeding trial experiments or from calorimetric measurements. Feeding trial estimates were higher than those derived from calorimetric studies. Balnave and Jackson (1973) have shown that the bird's energy requirements are greatly influenced by the feeding method and that ME intake may be decreased by restricted feeding without seriously affecting overall performance.

Metabolized water from feed was estimated by Mitchell and Kelley (1933), cited by Stewart and Hinkle (1959), at about 48 percent of the weight of the dry matter in the consumed feed, plus the free and hygroscopic water in the feed. Ota and McNally (1961) used 54 percent (wet basis) weight of feed as the weight of water released when the feed is digested. This assumed that the ordinary moisture content of feed is 10 percent.

2.2.4 Age

Mitchell et al. (1927) noted that, "the metabolic activity of the newly hatched chick is much greater than that of the mature embryo". Mitchell et al. (1927), Romijn (1954) and Freeman (1964) have shown that the embryo is essentially poikilothermic, that is, body temperature tends to follow environmental temperature, but homeothermy develops rapidly immediately after hatching (Romijn, 1954; Freeman, 1964). Mitchell et al. (1927) and Barott and Pringle (1946) were the initial investigators of the relationship between age and bird heat production. The results obtained in these studies may be unreliable as no acclimatization period was allowed prior to placing the birds in the calorimeter.

The report of Mitchell et al. (1927) indicated that, "immediately after hatching, the starving heat production, based on metabolic body size, is considerably lower than that observed in the mature bird". Similarly, Burlacu and Baltac (1971) published data which indicated that, on a metabolic size basis, both the starving metabolic rate and the maintenance ME requirements, of 16 temperature-acclimatized White Leghorn pullets, decreased from 1 month of age until just before the commencement of lay, but increased during a subsequent 10-month perion of lay.

The results of Barott and Pringle (1946) suggest that the thermoneutral zone varies with age. These authors also reported that the evaporative heat loss is nearly constant up to the lower critical temperature. The results of this work and also those reported by van Kampen and Romijn (1970) and O'Neill et al. (1971) implies that at temperatures above 24°C evaporative cooling assumes importance for mature birds, although the actual temperature will depend on such factors as starving heat production, food intake, and strain.

2.2.5 Cover Insulation

Feathers provide the main form of insulation for the bird and, within the thermoneutral zone, they provide the major means of controlling the rate of heat loss from the body surface. Barott and Pringle (1946) observed that, "the degree of insulation may be adjusted by altering the spatial arrangement of the feathers and thus the depth of the insulating layer of air around the body". Therefore, the rate of increase in metabolic rate above or below the critical temperature is much more pronounced in the young than in the mature bird.

Hutchinson (1954) noted that, "although Leghorns have a closer plumage, that of Rhode Island Reds is thicker and, consequently, the insulation of the latter breed should be greater at low wind velocities". These results are in agreement with those of Ota and McNally (1961). These researchers reported that the total heat production and sensible heat loss at different temperatures was, on a body surface area basis, much greater for White Leghorn than for Rhode Island Red laying hens.

O'Neill et al. (1971) found that the starving heat production of defeathered cockerels only approached those of feathered cockerels at environmental temperatures above 34°C, while the differences increased rapidly as the temperature was reduced below 34°C. These data illustrate the important role that cover insulation plays in bird total heat production. Wathes and Clark (1978) reported that the conductance by sensible heat transfer of defeathered birds was about two or three times that of fully-feathered birds.

2.2.6 Effect of Movement

Any movement by the bird causes the entrapped air between the feathers and skin to be disturbed and total heat loss is increased. Deighton and Hutchinson (1940a,b) observed a reduction in metabolism of 12 percent when the bird was asleep with head-under-wing compared with that in the sitting position. These investigators also reported that the total heat production in the standing position was approximately 42 percent above that in the sitting position. DeShazer et al. (1970), as cited by Scott et al. (1983), similarly reported a 20 to 40 percent increase in sensible heat loss in the standing compared with the sitting position. Mitchell and Kelley (1933), as cited by Stewart and Hinkle (1959), stated that the extra heat produced due to activity can be estimated by assuming it equal to approximately one-half the basal heat value.

Recent studies have shown that the activity resulting from feeding and general movement decreases during darkness. Feddes et al. (1984b) found a mean reduction in day-to-night total heat production of 17 percent for three commercial laying barns in Alberta. Similarly, Ota and McNally (1961) reported a value of 30 percent, for Rhode Island Red and White Leghorn laying hens, at temperatures between -4 and +32°C. However, the average day-to-night reduction for White Leghorn laying hens maintained at a constant temperature of 18.0 to 19.4°C was only 16 percent.

DeShazer and Mather (1981) reported on the initial heat losses of 18 to 20-week old pullets grouped at different cage densities. The sensible heat loss of these pullets increased approximately 30 to 18 percent as density increased from 1 bird per 20.3 x 40.6 cm cage to 2 or 3 birds per 30.5 x 40.6 cm at environmental temperatures of 30 and 35°C, respectively. Evaporative heat loss did not change significantly.

2.2.7 Genetic Influences

Maintenance energy (or basal heat production) of birds (King and Farner, 1961) or mammals (Kleiber, 1975) has been related to the three-quarters power of body weight. However, this same power may not be appropiate for comparisons between individual birds within a flock or between flocks, whether of the same or different strains, differing in body weight. Tasaki and Sasa (1970) found that body weight was better than the three-quarters power of body weight, as a base, in similar comparisons. Tasaki and Sakurai (1965) proposed that differences in metabolism of crossbreed birds may arise as a result of variations in plumage type and temperament. Waring and Brown (1967) found the difference in metabolic rate to be 19 percent higher in laying than in non-laying hens while Tasaki and Sasa (1970) reported a value of 26 percent.

Waring and Brown (1965, 1967) estimated the maintenance energy requirements for white strains (White Leghorn) to be 481 kJ/(kg.d) and for brown strains to be 376 kJ/(kg.d), at a temperature of 25°C. The value for white strains is in good agreement with direct measurements (van Es et al., 1970; Grimbergen, 1970; Tasaki and Sasa, 1970; Burlacu and Baltac, 1971) and indirect estimates (Marsden et al., 1973; Smith and Oliver, 1972a, b; Jackson, 1972; Emmans and Dun, 1973).

2.3 Physical Influences on Poultry

The total heat production of the bird is equal to the total heat loss when there is a constant body temperature. The body temperature increases or decreases depending on whether the total heat production is greater or less than the total heat loss, respectively. Van Kampen (1974) considered that the contribution due to urinary nitrogen (N), under normal conditions, to the total heat production of the bird was negligible.

Romijn and Lokhorst (1961) derived a formula relating the amount of total heat production to the combustion of carbohydrates, fats, and proteins. This formula was later amended by the European Association for Animal Production (Brouwer, 1965; Blaxter, 1970). Heat is liberated during the combustion of carbohydrates, fats, and proteins and the total amount of heat production can be determined from the following equation:

$$H = 16.18\ O_2 + 5.02\ CO_2 - 1.20\ N \qquad (1)$$

where H = total heat production, kJ,

O_2 = oxygen consumption, L,

CO_2 = carbon dioxide production, L, and

N = urinary nitrogen, g.

2.3.1 Total Heat Production

Poultry heat and moisture production data for engineering design purposes are given in a number of widely used references, including the Canadian Code for Farm

Buildings (1977), the A.S.A.E. Yearbook of Standards (1983) and the Midwest Plan Service Structures and Environment Handbook (1983). These sources, however, do not include data for birds being reared as replacements for egg laying operations. In addition, there are sufficient differences in bird type and housing and management practices to make extrapolations of broiler and layer data highly questionable for use as criteria in designing environmental control systems in poultry rearing units.

Many studies have been carried out to investigate the total heat production of poultry. However, a comparison of the results is limited due to inconsistency or lack of sufficient data. Hence, van Kampen (1974) proposed the term basal metabolic rate (BMR) to form the basis for a comparison of results and defined this term as the rate of metabolic free energy production of an animal in a completely rested, awake, fasting (postabsorptive), and thermoneutral state. Dukes (1937), as cited by van Kampen (1974), stated that the BMR is attained 24 to 30 hours after withdrawal of food.

The total heat production per kilogram liveweight was reported by Ota and McNally (1961), for White Leghorn hens, to range from 14.9 to 24 kJ at temperatures of 32 to -4°C. Romijn and Vreugdenhil (1969) reported that the total heat production decreased continuously in laying hens as the ambient temperature increased from -10°C to +40°C. O'Neill et al. (1970) discovered similar results. In similar tests, van Kampen and Romijn (1970) developed a quadratic equation relating total heat production to ambient temperature.

2.3.1.1 Humidity and Temperature Effects

Van Kampen (1981) outlined the methods available to poultry for maintaining homeothermy when humidity is raised at temperatures above 25°C. This balance may be achieved by, "lowering the insulation of the feathers, by reductions in heat production and hence food intake, by raising body temperature or by increased ventilation of the respiratory tract". This author concluded that an increase in humidity would have a similar effect as an increase in ambient temperature.

Reece et al. (1972) noted that relative humidity had an insignificant direct effect on broilers for ambient temperatures ranging from 10 to 26.7°C but became crucial to life when the ambient temperature approached body temperature. Barott and Pringle (1951) obtained similar results for adult hens. Boone and Hughes (1971) reported that, between an ambient temperature of -5 and 25°C, the body temperature is practically constant, but rises when the environmental temperature exceeds 30°C. They also noted that the body temperature is higher during the day than during the night, whereas at temperatures of 35°C and higher the reverse is true.

2.3.1.2 Wind Factor

Air movement causes the air temperature to be less than skin temperature by reducing the boundary layer around the body. Siegel and Drury (1968) observed that total heat loss increases when the skin temperature exceeds the air temperature, but body temperature may be raised if the reverse is true, when the only way the animal can lose heat is by evaporation. To quote van Kampen (1981):

> "Increasing air velocity when the ambient temperature is above the critical temperature but below body temperature will reduce heat stress. However, below the critical temperature such an increase in heat loss results in an increase of heat production and therefore of food intake and, if the ambient temperature is very low, loss in body weight".

Siegel and Drury (1968) postulated that the bird's metabolic rate would increase at high wind speeds if air velocity were to have an important influence on total heat loss from the feathered body. However, Boone and Hughes (1971) were unable to substantiate this concept and also were unable to find a significant correlation between wind speed and body temperature. They concluded that the bird's heat loss is little influenced by air movements and that the feathers provide a windproof protection.

2.3.2 Sensible Heat Loss

Sensible heat exchange between the animal and its surroundings takes place through the three channels of conduction, convection, and radiation. The heat loss from the homeotherm finally is determined by the ambient environmental conditions while the homeotherm itself has an influence on the amount of heat produced, the heat transfer to the body surface, and the insulative effect of the cover.

Heat loss by conduction occurs when energy is exchanged by solid surfaces in contact with one another. Conductive heat transfer, as explained by Curtis (1981), is comprised heat flow by convection through the blood stream, conduction by the tissues from core to skin, and by conduction through feathers to the covers surface, which is in contact with the environment. Bruce (1981) noted that heat transfer by conduction through contact with solid surfaces is an important factor for animals that lie on the ground or on the floors of buildings and enclosures. This conductive heat transfer is a function of contact area and temperature and the thermal conductivity of the material.

Convective heat transfer is a form of heat transfer that takes place at the surface of a solid body in a fluid medium (air) under the influence of a temperature differential. Therefore, convective heat transfer is a function of the surface temperature of the body, its size, configuration and thermal conductivity, and on the ambient air conditions and movement. Mount (1979) outlined two different kinds of convective heat transfer. Free or natural convective heat transfer is due to a density difference between thermally inhomogeneous fluids. Forced convective heat transfer is due to pressure differences induced by external forces impinging on the fluid. Forced convection dominates when the body is subjected to high air velocities while natural convection dominates in still air or at low wind speeds.

Thermal radiation refers to the heat transfer, by electromagnetic waves, between two surfaces due to a temperature differential, and without the aid of a material medium. These waves occupy two distinct wavebands at opposite ends of the thermal radiation spectrum, that is, short-wave and long-wave radiation. Short-wave radiation is emitted by the sun (ASHRAE, 1978) and absorbed and reflected by various earthly bodies. Mount (1979) noted that for short-wave radiation the reflectance of a body is influenced by the color of the body while for long-wave radiation color was not a factor.

A major component of the animals' sensible heat loss is that due to heat emission by long-wave radiation. Cena (1973) defined the net radiation exchange as, "the difference between the total radiation absorbed by a surface and the total radiation emitted and reflected". Mount (1979) observed that long-wave radiation does not pass through most of the substances that are transparent to the shorter wavelengths of the visible spectrum. Long-wave radiation exchange between two bodies is governed by the Stefan-Boltzmann Law, which states that the heat transfer rate by radiation is equal to the product of a constant and the difference between the fourth powers of the respective absolute temperatures. The quantity of heat loss by radiation is determined by the absorptivity, emissivity, area and temperature of the body surfaces. ASHRAE (1978) defined absorptivity and emissivity as the capacity of a material to absorb and reflect radiant energy, respectively.

2.3.3 Evaporative Heat Loss

When the ambient temperature is warmer than an animals surface temperature, total heat produced is greater than total heat lost. The animal dissipates this extra heat to maintain homeothermy by increasing evaporative heat loss - a process that mainly is a function of a water vapor-pressure gradient. In hot environments, Curtis (1981) outlined the pathways of increasing evaporative heat loss as either increasing the respiration rate or increasing the amount of water on the skin by sweating or wallowing.

The chicken increases its respiratory rate when under the influence of mild heat stress. Subsequently, breathing frequency increases and more of the respired air passes over the alveolar membranes. Consequently, according to Curtis (1981), "chickens under extreme heat stress also experience mild respiratory alkalosis". Birds have no sweat glands, but in many panting birds, as stated by van Kampen (1974), heat loss by evaporation does not exceed 50 percent of their metabolic heat production. However, Lasiewski et al. (1966) found that many birds, under low vapour tension, maintained their body temperature below environmental temperatures of 44 to 46°C for periods ranging from 1 to 4 hours by evaporative cooling.

Above an ambient temperature of 25°C, cover insulation hinders the pathway for evaporative heat loss. Consequently, heat flow by circulatory convection will be directed more to the head appendages (van Kampen, 1974; van Handel-Hruska et al., 1977). Richards (1976) noted that evaporative heat loss decreases with rising ambient water vapour pressure.

Van Kampen (1976), as cited by Scott et al. (1983), reported that the respiratory evaporative heat loss of chickens, at high air temperatures, only reached 23 percent of its original value when the relative humidity was increased from 40 to 90 percent. These authors concluded that relative humidity had no affect on bird production losses at 20°C. Researchers observed the effect that temperature acclimation to 35°C from 25°C had on the evaporative heat loss of birds. Van Kampen (1976), as cited by Scott et al. (1983), found a reduction of 17 percent in 9 days from 2.3 to 1.9 g $H_2O/(h.kg)$ while Roller and Dale (1963) reported a value of 66 percent in 11 weeks from 7.0 to 2.6 g $H_2O/(h.kg)$. Mitchell and Kelley (1933), as cited by Stewart and Hinkle (1959), estimated that the percent of total heat appearing as latent heat increases exponentially with the environmental temperature.

2.3.4 Lighting Specifications

The activity and physiology of birds is influenced greatly by light. Siopes (1982) outlined the, "functions of light as:

1) synchronization of rhythmic functions, and
2) induction of hormone synthesis."

Siopes (1982) also thought that birds perceived light through eyes, feathers, skin and bone and through to the brain which subsequently influences hormone production and activity. Birds utilize the available light within their environment to increase production and, thus, the lighting schedule within poultry barns is associated with improved biological efficiency (production performance) and physical efficiency (energy saving).

2.3.4.1 Photoperiod

Curtis (1981) defined photoperiod as the period of time when there is light present. Morris (1977) developed from available data an equation relating age of pullets in days at sexual maturity (A) to constant photoperiod in hours (P):

$$A = 170.2 - 1.610P + 0.00061P^2 + 0.001918P^3 \quad (2)$$

Thus, according to equation 2, for a 10-hour constant photoperiod during rearing the pullets would be expected to lay their first egg at 155 days of age. Morris (1967) recommended a ten-hour constant photoperiod during rearing and laying for maximum egg production. In addition, Morris (1962) claimed that bird age at sexual maturity was more influenced by the rate of change of photoperiod than on absolute photoperiod at a particular time during rearing. Morris and Fox (1960) reported that a step-down lighting program during rearing, "results in slower growth, later sexual maturity, heavier mature weight, larger eggs, and higher annual egg production".

2.3.5 Restricted Feeding

The purpose of restricted feeding, according to Harms (1982), is to delay sexual maturity and increase egg size. Investigations involving restricted feeding of pullets have shown a delay in sexual maturity (Sherwood and Milby, 1954; Milby and Sherwood, 1956; Davis and Watts, 1955; Gowe et al., 1964; Deaton and Quisenberry, 1963; Strain et al., 1965), increase in mortality (Gowe et al., 1964; Deaton and Quisenberry, 1963; Strain et al., 1965), reduced body weight (Gowe et al., 1964; Deaton and Quisenberry, 1963; Strain et al., 1965), and had no significant affect on egg production (Davis and Watts, 1955; Deaton and Quisenberry, 1963). Novikoff and Biely (1945) reported that the restricted feeding of pullets increased manpower requirements and reduced growth and egg production.

Walter and Atkins (1961) reported on the difference between restricted and full-feed techniques during the growing period. They observed that the restricted-fed birds started laying later than the full-fed birds but egg production rates were higher at the end of the period for the former than those of the latter. Miller and Sunde (1975) noted that a decreased lighting schedule delayed sexual maturity more than feed restriction alone. Christmas et al. (1982) found a reduction in body weight of fall-housed pullets that were fed a low protein diet but their performance was not greatly influenced. However, Douglas and Harms (1982) concluded that feeding similar diets to spring-housed pullets caused a reduction in egg production and egg weight throughout most of the production cycle.

2.3.6 Housing Systems

Floor space and stocking density grew increasingly important in poultry production when the commercial egg farm became popular. This resulted in mechanized cage systems which reduced labour requirements. The introduction of mechanical ventilation systems, as noted by Wildey (1982), in confinement poultry units facilitated high stocking densities in areas prone to climatic extremes. In Canada, Murray and Mitchell (1980) claimed that more than 95 percent of the commercial egg producers utilized environmentally and light-controlled, caged units in conjunction with mechanized equipment.

2.3.6.1 Floor versus Cage Systems

Many researchers have observed decreased egg production rates when the numbers of birds in a cage were increased (Adams and Jackson, 1970; Bell et al., 1979; Champion and Zindel, 1968; Emmans, 1971; Feldkamp and Adams, 1973; Foss and Carew, 1974; Quisenberry and Bradley, 1964; Rose and Sell, 1969; Ruszler and Quisenberry, 1970; Sefton, 1976; Wells, 1971).

Johnson and Zindel (1961) observed that layers in cage facilities had higher egg production rates than those housed on litter or slatted floor. Gowe (1956) and Lowery et al. (1956) observed better production, over a four-year period, in floor-housed birds than in cage layers. Conversely, other investigators found superior production from birds in cages (Miller and Quisenberry, 1959; Bailey et al., 1959; Rose and Sell, 1969). Wells (1971) suggested that colony size appeared to be more important than space per bird in terms of both productivity and bird welfare. Sefton (1976) found reduced egg production when the number of birds per cage were increased and area per bird decreased.

2.4 Air Quality

Air quality refers to the quantity of air contaminants within the barn environment and the possible effect these contaminants may have on the inhabitants. Air within a confinement building contains numerous pollutants in various combinations and concentrations. These air contaminants in poultry units originate from the stored waste and birds. Nonruminants such as pullets produce CO_2 as a result of metabolism while ruminants, in addition, produce CH_4. The stored waste undergoes biological degradation and, subsequently, NH_3, H_2S, in conjunction with CO_2 are given off. Taiganides and White (1969) also noted that moisture was present in the waste and produced by the birds.

The composition by volume of dry, outside air is approximately 78.09% N, 20.95% O_2, 0.93% argon (Ar), and 0.03% CO_2, with slight traces of inert gases (Jorgenson, 1983). Scott et al. (1983) identified other trace gases generated from the animal waste but did not consider these of any significance to animal productivity. ASHRAE (1981) classified particles greater than 1μm as dust and less than 1μm as fumes. Most of the particulate matter in confinement units are generated from feed and surfaces of animals.

Traditionally, gases were considered (Taiganides and White, 1969) to distribute within a confinement unit according to their relative densities, that is, lighter gases, such as NH_3 and CH_4, would rise from the point of generation and accumulate near the ceiling. This concept has been disproved by more recent studies (Brannigan and

McQuitty, 1971; Feddes and McQuitty, 1973; Noren et al., 1967; Robertson and Galbraith, 1971). Brannigan and McQuitty (1971) reported that sensible heat was a major factor in the diffusion of gases in the atmosphere.

Air flow within an animal unit should be capable of removing most of the air contaminants and replacing them with fresh outside air, while avoiding drafts around the animals. Therefore, this aspect should be given considerable attention when deciding the building layout and the air inlet system.

2.4.1 Air Contaminants

Unfortunately, actual data on gas concentrations in animal barns under Canadian conditions are either unavailable or are such that their applicability for use as design criteria for environmental control purposes is questionable. Available information is based almost entirely on work carried out in Europe and the U.S.A. and is, in itself, incomplete in many respects and widely scattered, as indicated in several literature reviews including those of Nordstrom and McQuitty (1976) and Scott et al. (1983). Thus, caution must be exercised in interpreting the data as being valid under Canadian conditions. At best, only an approximation of the situation can be assumed.

2.4.1.1 Carbon Dioxide

To quote Scott et al. (1983), "Carbon dioxide is odorless, colorless and 1.5 times heavier than air." Carbon dioxide production is a function of metabolic rate and is directly related to total heat production. Therefore, as stated by Scott et al. (1983), "CO_2 production is a function of animal weight, level of feeding and thermal environment".

McQuitty and Feddes (1982) commented that CO_2 concentrations experienced in normally-ventilated barns were in the 500 to 4000 ppm range. Leonard et al. (1984b) and McQuitty et al. (1984) also found winter concentrations of CO_2 of not more than 4000 ppm in, respectively, two broiler units and three layer units. Taiganides and White (1969) claimed that, under winter conditions, CO_2 concentrations may reach 5000 or 6000 ppm but did not consider these levels to be detrimental to the birds health and performance.

Curtis (1981) outlined the effects of different CO_2 concentrations on animals. He stated that the animals respiration rate increases when exposed to concentrations of 50,000 ppm but no other significant effects were evident. When the concentration exceeds 400,000 ppm, "the animals witness anxiety, followed by staggering, coma, and finally death". Helbacka et al. (1963) reported that, at CO_2 concentrations of 50,000 ppm, laying hens showed signs of distress, had a depressed appetite and a reduction in egg shell thickness. The birds health and production returned to normal when the birds were no longer exposed.

2.4.1.2 Methane

Methane is colorless, odorless, not very soluble in water, much lighter than air and highly flammable (Taiganides and White, 1969).

Under normal conditions, CH_4 is relatively safe but its presence was considered by McQuitty and Feddes (1982) to be a potential safety hazard to humans, animals and property. This consideration was due to the flammable and explosive nature of CH_4, particularly at concentrations of 5 percent and higher in air. Johnson (1981), as cited by McQuitty and Feddes (1982), commented on a number of incidences that were related to such hazards in animal barns. However, CH_4 is not a critical problem in monogastric confinement units such as poultry barns except when the manure or droppings pits are agitated.

2.4.1.3 Ammonia

Ammonia is colorless, soluble in water, lighter than air, and has a pungent odor (Taiganides and White, 1969). Concentrations of NH_3 appear to vary considerably in animal barns, although the reasons for this have not been assessed.

In poultry studies, a concentration of 100 ppm has been shown to cause symptoms of keratoconjunctivitis

(Charles and Payne, 1966a,b). The same study revealed that this concentration of NH_3 caused a decrease in egg production. Concentrations of 20 ppm were found to cause damage to the respiratory tract (Anderson et al., 1964), although no histopathological changes were evident until the sixth week of exposure. These authors also observed that concentrations of 1000 ppm resulted in the birds developing photophobia and crowding in dark corners to avoid light.

Bullis et al. (1950), as cited by Lampman (1982), and Valentine (1964) demonstrated that a prolonged exposure to 60-70 ppm of NH_3 caused keratoconjunctivitis, reduced growth rate, and increased feed conversion. Curtis (1981) noted similar results for broilers and replacement pullets exposed to 75-100 ppm of NH_3. He found a reduction of as much as 15 percent in growth rate but feed-conversion efficiency remained the same.

Leonard et al. (1984b) recorded, under winter conditions, a mean ambient NH_3 concentration of 6 ppm in two broiler barns (range: 2-12 ppm) while McQuitty et al. (1984) reported mean values over a four-month winter period in three layer units as high as 53 ppm. Higher NH_3 concentrations at animal level can be anticipated during agitation of manure pit contents. Gaspar et al. (1961) reported unilateral blindness in chickens exposed to approximately 45 ppm of NH_3 for a period of 12 weeks.

2.4.1.4 Hydrogen Sulphide

Hydrogen sulphide is colorless, water soluble, heavier than air and has a rotten-egg odor (Taiganides and White, 1969). Hydrogen sulphide is a very toxic gas and is generated from the putrefaction of organic wastes. Low aerial concentrations of H_2S irritate the eye and respiratory systems of animals. Curtis (1981) claimed that, at moderate concentrations, animals become more sensitive to light and their respiratory systems become susceptible to infections.

Hydrogen sulphide concentrations were considered by McQuitty and Feddes (1982) to be minimal in many commercial confinement animal units. Leonard et al. (1984b) and McQuitty et al. (1984) investigated, under winter conditions, prevailing H_2S concentrations in commercial poultry barns. They found no detectable H_2S in two broiler units and a maximum concentration of only 30 ppb in three layer units monitored, respectively. Petrov (1966) found a 9 percent reduction in egg production when hens were exposed for two months to an ambient atmosphere containing 5000 to 9000 ppm CO_2, 80 to 100 ppm H_2S, and 52 to 80 ppm NH_3.

Donham et al. (1977) warned of the dangers involved when manure pits are agitated; sudden releases of H_2S may lead to a lethal environment. Values resulting from this disturbance appear to range from only a few ppm, as may occur in the case of gutters cleaned regularly, to several hundred ppm, when pits are being emptied. McAllister and McQuitty (1965) noted that agitated poultry slurry may release concentrations of H_2S ranging from only 2 to 1000 ppm. Ludington et al. (1969) concluded that H_2S production was considerably more in chicken manure stored in a diluted state than in an undiluted state but release of the H_2S only was twice as fast. Factors controlling H_2S production and its release have been reviewed by Barber and McQuitty (1974).

2.4.1.5 Dust

Scott et al. (1983) classified dust as; "particles greater than 1μm in diameter and less than 150μm while fumes ranged from 0.1μm to 1.0μm". Lampman (1982) presented a chart relating the particle sizes of different atmospheric impurities and defined "dust causing lung damage" in the size range of 0.5μm to 6μm. Dust particles less than 10μm will tend to diffuse in still air and remain suspended. Aerodynamic diameter (used to define particulate size) is "the diameter of a hypothetical sphere of unit density having the same terminal settling velocity as the particle in question regardless of its geometric size, shape and actual density" (Honey and McQuitty, 1976).

In poultry houses, Curtis (1981) concluded that dust in poultry units consisted of feather and skin debris, including particles from the feed and litter. In addition, Curtis (1981) commented on dust concentrations as affected by housing systems. He claimed that dust contains over 50 percent and 80 percent crude protein in cage layer houses and litter-floor houses, respectively. From 10 to 20 percent of the dust in cage layer houses comes from the feed. Curtis (1981) also suggested that the dust in litter-floor poultry houses comes mainly from the birds themselves, with small contributions from the feed and the litter.

Curtis (1981) and Grub et al. (1965) claimed that dust generation in poultry houses was influenced by bird strain and age, litter and feed type, housing type, bird density and activity, and environmental conditions. Lillie (1970) noted that dust particles can absorb gases and liquids, carry viruses and bacteria, and serve as a carrier for Marek's disease. Cage birds, according to Grub et al. (1965), produce 10 to 25 percent less dust than birds on litter.

Longhouse et al. (1960) stated that the amount of dust in the air increases when the litter moisture content decreases below 20 percent wet basis. An excessive amount of moisture in the litter contaminates feeders and waterers. These authors also observed that the NH_3 production from litter decomposition commences at 17 to 19 percent moisture content and recommended that litter moisture content should be kept below 33 percent wet basis.

2.4.2 Animal and Human Health and Welfare

There is a lack of information available on allowable levels of air contaminants in animal buildings under varying conditions. Acceptable levels of gas concentrations for humans, or threshold-limit values (TLV), have been applied to an animal situation, but these values must be treated with caution. More data is required to determine the interaction between animals and the gaseous environment under commercial conditions because the time-weighted TLVs for humans have been defined by ACGIH (1984) and are based on a maximum 8-hour day, 40-hour week exposure to a single gas.

However, animals in total confinement are subject to their environment continuously and may face a number of potentially harmful air contaminants simultaneously. This dilemma has enabled Bruce (1981) to suggest that, for example, TLVs of 3000, 20 and 5 ppm for CO_2, NH_3, and H_2S, respectively, might be acceptable in the case of pigs for normal design purposes. Similar TLVs might be adapted in poultry facilities. The corresponding TLVs in the industrial workplace are 5000, 25 and 10 ppm, respectively (ACGIH, 1984). The time-weighted TLVs for nuisance dust, as suggested by ACGIH (1984), are 1060 particles/mL but are reduced to 420 particles/mL if the air contains particles less than 5μm in diameter.

McQuitty and Feddes (1982) considered H_2S as the most lethal manure gas in confinement units. Blaxland et al.

(1978) proposed manure agitation or disturbance as the common denominator in known and suspected H_2S poisonings in animal units.

Donham et al. (1982) reported that liquid manure gases exposure form a serious, and sometimes lethal, threat to both operators and/or animals. McQuitty and Feddes (1982) suggested that H_2S was the primary factor associated with these deaths and that, "most are associated with agitation and/or emptying of liquid storage tanks or pits". Osbern et al. (1981) noted that most of these accidents occurred due to carelessness, especially during emptying of manure pits.

A good literature review on the effects of exposure of NH_3 on poultry has been presented by Nordstrom and McQuitty (1976). Anderson et al. (1964) reported that chickens became susceptible to infection of Newcastle disease when they were exposed continuously to 20 ppm of NH_3. Exposure of pullets to 53 and 78 ppm NH_3 from 11 through 46 weeks of age significantly increased age at sexual maturity by one and two weeks, respectively (Charles and Payne, 1966a,b). Lampman (1982) commented that,

> "According to Bullis et al. (1950), Longhouse et al. (1963) and Lampman et al. (1967), NH_3 production in poultry houses depends on the amount of fecal matter in the litter, litter moisture content, temperature, humidity, ventilation rate, floor space per bird and the season of the year. The symptoms of NH_3 toxicity include watery eyes, closed eyelids, rubbing of the eyes on the wing, decreased growth rate, poor feed conversion and huddling of affected birds."

McQuitty and Feddes (1982) stated that animal fatalities occurred, in confinement units with little infiltration, due to heat stress and high CO_2 concentrations present in conjunction with a breakdown in the mechanical ventilation system. Honey and McQuitty (1976) noted the lack of information on the direct adverse effects of dust on lungs in animals and they concluded that "it is a significant contributing factor in animal health" due to its association with other contaminants. In addition, studies by Harry and Hemsley (1964) and Carlson and Whenham (1967) indicated the presence of organisms in poultry house dust which act as agents in chronic respiratory diseases.

Prince et al. (1971) also reported that poultry house dust was a major source for the transmission of Marek's disease, a highly contagious disease of young chickens. Jurajda and Klimes (1970) further confirmed this when collecting samples of dust from poultry house ventilation ducts. A method for controlling dust in the animals environment was proposed by Drury (1970) who reported on a filtered-air, positive-pressure, ventilation system that was utilized to control Marek's disease and infectious bronchitis.

Donham et al. (1977) and Donham and Gustafson (1981) identified other potential human occupational health hazards associated with total confinement animal operations. These hazards are of a respiratory nature arising from "the presence in the work environment of gaseous products of anaerobic digestion of manure and high levels of aerosolized particulates". Poultry confinement operations apparently do not "elicit adverse symptoms in workers nearly as frequently or severe as swine confinement".

3. OBJECTIVES

The Department of Agricultural Engineering at the University of Alberta, has developed over the past few years, the means to monitor thermal and non-thermal parameters in large-scale commercial livestock housing units. Using this capability, two commercial replacement pullet units were monitored with the following objectives:

1. To determine the total heat output of pullets in two typical poultry rearing barns, one using the floor-rearing system and the other cage-rearing.
2. To establish the moisture load to be removed by ventilation and the percentage of the total heat produced by the birds that is vented as latent heat.
3. To quantify the extent of conversion of sensible heat inputs to latent heat within a replacement pullet unit.
4. To establish the rates of production and/or base line data for the primary air quality parameters, that is, CO_2, H_2S, NH_3, and dust, in these rearing units.
5. To determine the influence, if any, of management practices on these parameters.
6. To report on findings that may be useful for extension purposes in replacement pullet units.

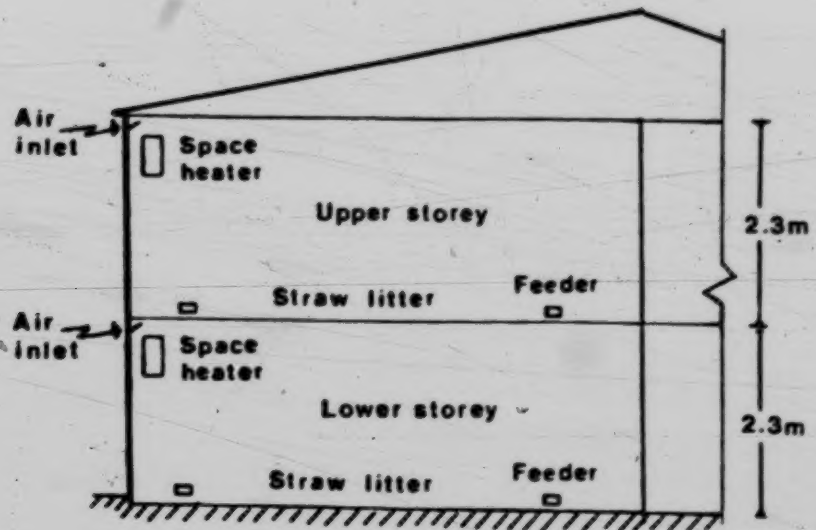
4. EXPERIMENTAL METHODOLGY

4.1 Facilities

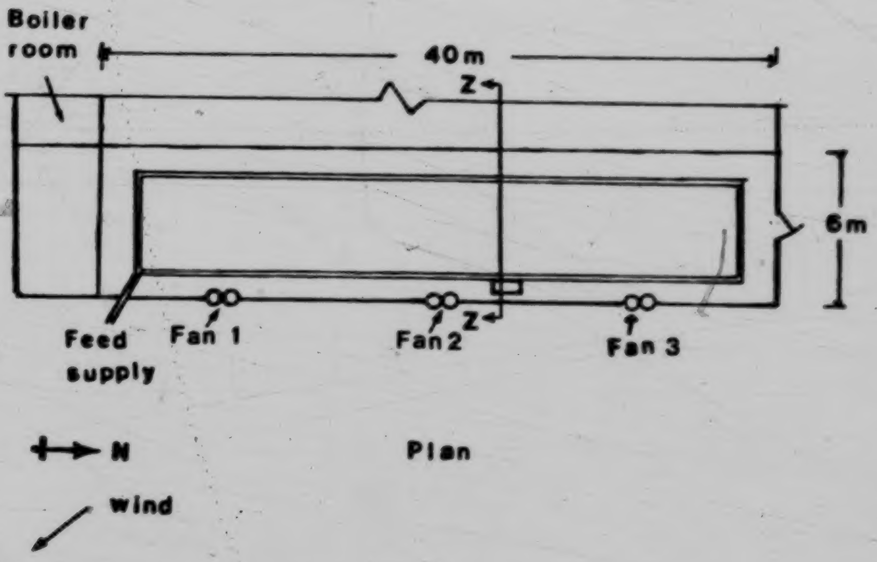
Two replacement pullet barns, were monitored to determine the heat and moisture production and air quality within these units under practical operating conditions. This necessitated the selection of barns already in production, which were examined with as little disruption to the normal routine as possible. The two units were selected for monitoring on the basis of feasibility of instrumentation, accessibility, and co-operation of the farmers. The study was conducted during the period extending from September 23, 1983 to April 13, 1984.

The most critical factor in the evaluation of potential barns was the feasibility of monitoring them. This condition precluded the use of very large or poorly sealed buildings in which accurate measurement of temperatures, air quality, and air flows would not be practical. A brief description of both units monitored follows.

Barn A measured 6 by 40 metres with a ceiling height of 2.3 metres (Figure 4.1). Barn B measured 9 by 50 metres with a ceiling height of 2.4 metres (Figure 4.2). Barns A and B were located 8 km south of Thorsby, Alberta, and 10 km south-west of Stony Plain, Alberta, respectively. The replacement pullets in Barns A and B were of the Hy-line W-77 and Shaver S288 strains, respectively, both similar

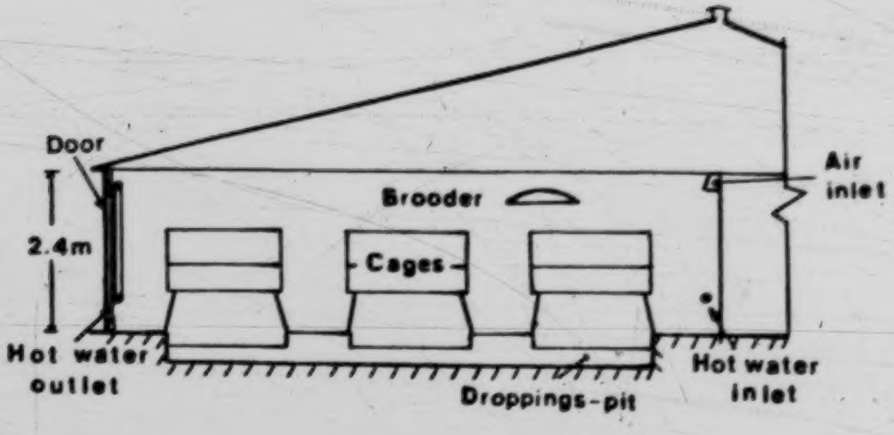


Elevation – Section ZZ



Plan

Figure 4.1 Schematic diagram of Barn A.



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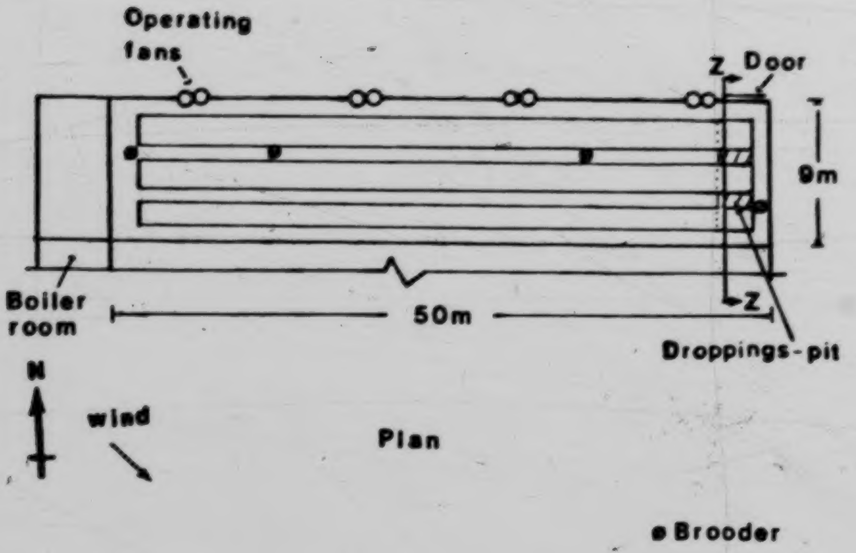

Plan

Figure 4.2 Schematic diagram of Barn B.

to the White Leghorn breed. Table 4.1 compares the management data for the two barns, including the number of birds housed and stocking densities.

Barn A was a double-storey, on-floor replacement pullet unit. Initially, 5825 day-old chicks were placed in the upper level, with over half of the birds being moved to the lower floor after six weeks. Only the upper storey of the barn was monitored, as the bottom storey was identical in design and management techniques to the upper storey. The production cycle, on fresh straw litter, was initiated on September 13, 1983 with the arrival of the chicks. The litter was cleaned out, after the pullets were removed to the layer barns, by a gasoline-powered front-end loader. This litter was deposited out the end door on the north wall, where it was conveyed to a nearby lagoon by a heavy-duty, tracked loader.

Barn B, a single-story unit, utilized six rows of double-deck rearing cages. Initially, 14000 chicks were placed in the lower level of cages. After six weeks, they were divided evenly among both decks. The production cycle commenced on November 29, 1983. Initially, 24 pullets were placed in each of the bottom cages with a cage area per bird of 231 cm^2. After 6 weeks, each cage contained 12 birds with a cage area per bird of 463 cm^2 (Table 4.1). The recommended cage area for replacement pullets up to and after 6 weeks is 160 and 280 cm^2 per bird, respectively (Canadian Code for Farm Buildings, 1977) and, consequently, the stocking

Table 4.1 SUMMARY OF MANAGEMENT DATA FOR THE TWO BARNS.

BARN	A	B
Number of birds: start/finish	5825/2323[3]	14000/13580
% mortality	8.3	3.0
Birds per cage	-	24 (12)[1]
Size of cage, cm^2	-	91 x 61
Cage area per bird, cm^2/bird	-	240 (450)[1]
Bird density, birds/m^2 floor area	24 (10)[1]	27
Building exposure factor, kJ/(h.°C.bird)	0.05 (0.12)[1]	0.13
Heating system	hot water	hot water
Automatic feeder type	Chain - in - trough	
Frequency[2] of feeder operation per day	7	2
Manure handling system	tractor	shallow gutter
Lights on/off (L:D), hours	0700/1800 (11:13)	

[1] After six weeks
[2] Light period only
[3] Upper storey only

density in this unit could have been increased. Below the cages were shallow concrete droppings pits, 150 to 200 mm in depth, which were scraped mechanically to the east end of the barn (Figure 4.2) and moved outside by a cross-conveyer into a tractor-powered, liquid manure tanker. Removal of the droppings from the barn normally was carried out every 10 weeks.

Barns A and B were attached on their windward and leeward sides to a double-storey/deep-pit layer unit and a triple-deck/shallow droppings-pit layer unit, respectively. Henceforth, reference to barns or buildings in this study only apply to the replacement pullet rooms. The mortality rate over the rearing cycle was 8.3 and 3.0 percent, respectively. During the second monitoring period in Barn A, over 200 birds piled up in one corner of the barn and suffocated. The temporary switching over from normal lights to blue-colored lights may have alarmed the birds and resulted in this pile-up. Two 25-watt blue-colored lamps were installed in Barn A for the first two runs to facilitate mobility of researchers inside this unit without undue danger to the birds. These lights were switched on during the monitoring period while the normal lights were switched off. During this period the birds remained calm and did not appear to be aware of the researchers presence within the barn. To prevent similar incidences in the future the author suggests that the blue-colored lights are switched on before the normal lights are switched off or use dimmer switches.

The mortality rate in this barn was calculated, taking into account these deaths by apportioning them equally between the upper level and the lower level over the rearing cycle. Initially, the bird density, in Barn A, was 24 birds per m^2 of floor area. After 6 weeks, the density was reduced to 10 birds per m^2 while Barn B had a density of 30 birds per m^2 of floor area over the rearing cycle (Table 4.1). The Canadian Code for Farm Buildings (1977) recommends 16 (up to 6 weeks) and 8 (7 - 20 weeks) birds per m^2 floor area for on-floor rearing of pullets.

Both barns used exhaust ventilation systems, with the fans being located on the leeward and windward sides of Barns A and B, respectively. Fresh air was introduced directly into Barn A from outside through an intermittent, slotted, air inlet located under the eaves on the same side of the barn as the exhaust fans (Figure 4.1). In Barn B, fresh air was drawn into the attic via roof vents, and then into the barn through a continuous-slot, air inlet situated along the opposite wall of the room from the exhaust fans (Figure 4.2). This inlet was covered with a burlap hanger that directed the air towards the floor.

In Barn A, three variable-speed, 51-cm diameter fans were spaced equally along the length of the building. Two of the variable-speed control units, nearest to the south wall, were operated by the same thermostatic controller. The third fan in this unit was operated by a separate thermostatic controller. All three fans were located 1.7 m above floor level, and utilized anti-back draft louvers on the inside. Ventilation in Barn B was provided by four, 51-cm diameter, two-speed fans spaced approximately equally along the length of the barn. The fans were located 1.7 m above floor level and were each on a separate thermostatic controller. In addition, Barn B had five more 51-cm diameter, constant-speed fans spaced along the same wall to provide greater air exchange if required. These were not in operation during the study. Fan shrouds, composed of exterior-grade plywood, were utilized on the outside. A 91-cm diameter fan was located on the east wall, at bird level, to provide extra exhaust ventilation during the summer. The non-operating fans were sealed off during the winter to prevent them from acting as inlets due to the negative pressure prevailing in the barn.

Both of the barns studied were of insulated wood-frame construction, with metal roofs. The walls and ceiling were sheathed on the inside with plywood and insulated with glass fibre. The outside sheathing consisted of metal and exterior-grade plywood in Barns A and B, respectively. The total thermal resistances of the ceiling and walls were calculated by summing the thermal resistances of each individual material and air film. These values were obtained from Canadian Code for Farm Buildings (1977). The total values for the ceiling and walls in Barn A were estimated to be 4.6 and 3.9 $m^2.°C/W$, respectively, while the corresponding values in Barn B were 3.8 and 3.6 $m^2.{}^\circ C/W$, respectively. No perimeter insulation was used in either barn. Using the reciprocal of these total resistances, the structural surface area, and the number of birds, the building exposure factor in Barn A was calculated to be 0.05 and 0.12 kJ/(h.°C.bird) for up to and after 6 weeks, respectively (Table 4.1). The corresponding value for Barn B was 0.13 kJ/(h.°C.bird) throughout the rearing cycle. The building exposure factor reflects the bird density within the barn, the structural size, and the standard of insulation of the different structural components.

Barns A and B utilized a wooden (upper storey) and concrete floor, respectively. In Barn A, the floor was covered with a thin layer of short straw, which was compacted by the birds, feed equipment, waterers, and operator over the rearing cycle (Figure 4.1). In Barn B, the cages were mounted, at a height of 0.7 m above floor level, on metal footings and directly over the droppings pits (Figure 4.2).

The ridge of the roof on Barn A was oriented north-south, while that of Barn B ran east-west. The heat gain component due to solar energy was not measured in this study due to its insignificant contribution to the total building heat load under Canadian winter conditions as shown by Clark (1982) for swine barns.

Both barns utilized hot-water heating as a source of supplemental heat. This was provided by a natural-gas fired boiler located in an adjacent room within each unit. In Barn A, water was circulated through one loop of 51-mm internal diameter, white-painted, iron pipe mounted 200 mm from the ceiling on the leeward wall, to a fan-operated space heater located 23 m along one side of the barn and 600 mm from the leeward wall (Figure 4.1). Clear spacings between the two pipes and between the pipes and the wall were 75 and 160 mm, respectively. These pipes also branched down to a similar space heater midway along the leeward wall in the lower storey. The total length of pipe, in this unit, was 50 m and 4 m for the upstairs and downstairs, respectively. In Barn B, a 67-mm internal diameter, black-iron pipe ran around the circumference of the room, mounted 600 mm and 60 mm from the floor and wall, respectively (Figure 4.2). The total length of the pipe was 128 m. The hot-water boiler in each barn was controlled by a single thermostat. In addition to the hot-water heating, Barn B utilized four natural-gas fired brooders, mounted 300 mm from the ceiling (Figure 4.2), to maintain a comfortable thermal environment during the first week of the production cycle. The latent heat released by gas combustion in the brooders was negligible, as shown by Longhouse et al. (1968). A propane-fired air heater also was used at floor level, near the entrance during the first four days of the cycle.

Feeding systems in each barn were chain-in-trough type, and were controlled by a timer. In Barn A, the feeder was activated seven times daily for 5-minute intervals while, in Barn B, the feeders ran twice daily for 15 minutes (Table 4.1). In both barns, the feed was conveyed inside by auger from an outside bulk container. In Barn A, the feeder was placed on the litter, in a rectangular shape, at a distance of 1.3 m from each wall. This feeder was attached to a pulley system on the ceiling to facilitate removal of the litter during cleanout.

The replacement pullets in Barn A were fed a wheat-based ration (16-20% protein, 12.8 MJ/kg ME), supplied and analyzed by a commercial feed producer. The birds in Barn B were fed a similar type ration (16-19% protein, 11.7 MJ/kg ME), but the ration was formulated on-farm by the operator according to the specifications of a commercial feed producer and the analysis was based on standard values used by this producer. The operator in Barn B weighed some of the pullets at random, at regular intervals, to determine if the weight of the birds were close to the target weights specified by the Shaver Commercial Management Guide (1982). The amount of feed given to the pullets then was altered or remained the same to enable the birds to attain their target weights. The operator in Barn A relied solely on the commercial feed producer to provide the required ration.

Water in Barn A was provided by standard fountain waterers, while Barn B utilized low-pressure drinking cups. Throughout the production cycle in both barns, medication was administered to the birds through the watering system, to prevent the occurrence of diseases such as Newcastle disease.

Lighting in both barns was incandescent, and controlled by a dimmer and time-clock. The 25-watt lamps were spaced at 4 m on centres in both barns with the lamps in Barn B located down the walk aisles. These were in accordance with the recommendations given by Winchell (1982). Lights were turned on from 0700 hours to 1800 hours in both barns giving a light:dark ratio of 11:13 throughout the rearing cycle.

4.2 INSTRUMENTATION

The main equipment utilized in this study to monitor continuously the components of the heat and moisture balance and the air contaminants in both units was the data acquisition system developed by Feddes and McQuitty (1977, 1981). The heat and moisture components in these rearing barns comprised dry-bulb and wet-bulb temperatures, dewpoints, air and hot-water flow rates and conductive heat flows. The heat and moisture produced by the birds were dissipated by the ventilation system and through the structure. The building heat balance was maintained by heat gains from the growing birds and by supplemental heating when required to maintain desired ambient temperatures. The air contaminants were monitored by measuring the concentrations of CO_2, NH_3, H_2S and dust particles in both units.

For any particular monitoring period, all the instrumentation was mounted permanently on an equipment rack in an air-conditioned 3.5 x 8 m mobile laboratory. This laboratory was located as near to the poultry units as possible so that the air-sampling lines and extension cables relaying from the bird environment to the monitoring laboratory had minimal exposure to the outside environment. To ensure that the air samples were above their dewpoint temperatures, the air-sampling lines were drawn through a 100-mm diameter, electrically-heated conduit between the building and the laboratory. The temperature within this conduit was observed at regular intervals to prevent condensation in the sampling lines. The conduit was not heated under warm outside conditions.

The equipment in the mobile laboratory was allowed to reach operating temperature before each monitoring period. In addition, each instrument was calibrated to minimize errors in the data. Throughout each run, hand-held instruments were utilized to check the validity of the sensor readings displayed on the data logger. The signals from each sensor located in and around the barn were conditioned to a 1 to 10-volt range by amplifiers to make them compatible with the analog-to-digital converter in the data logger.

To calculate the heat and moisture contents of the air entering and leaving each barn, the dewpoints and the dry-bulb temperatures of the inlet and exhaust air were monitored. Air samples were drawn via plastic tubing from each operating exhaust fan location to an optical-condensation dewpoint hygrometer (Model 880, Cambridge Systems, Waterdown, Mass.) housed in the mobile laboratory. The manufacturers claimed that the hygrometer was accurate to within 1°C of the reading. Before each run the hygrometer was set to "test" mode to check if the needle rested on the balance point (4°C) and was reset if misaligned. In the hygrometer, the air samples were passed over a reflecting surface that was cooled electronically until condensation occurred, thereby interfering with the reflection of the light. However, accurate measurements could not be made by the hygrometer when the dry-bulb temperatures reached below -8°C and in such cases dewpoint data were obtained from the meteorological station at Edmonton International Airport. Any error involved in substituting these data were considered to be negligible due to the dryness of the cold outside air.

The main temperature-sensing device used in this study was the thermistor (UUB 31J1, Fenwal Electronics, Framingham, Mass.) which is a semi-conductor that exhibits a very sensitive change in electrical resistance to temperature fluctuations. The manufacturers claimed that these curved-matched thermistors were accurate to within 0.2°C over a temperature range from 0 to 70°C. They also supplied a logarithmic regression equation (Appendix A) relating ambient temperature to the resistance exhibited by the thermistors. These thermistors were connected in a constant-current circuit as shown in Figure A1 (Appendix A). The equation relating the resistance of the sensors to the output voltages also is given in Appendix A.

Using thermistors, dry-bulb temperatures were measured inside the replacement pullet units. To provide data representative of the bird environment, each barn was divided into six sections, thirds longitudinally and halves laterally. The wet-bulb temperatures were monitored at mid-height in the centre of both end sections. To obtain representative dry-bulb temperatures, a thermistor was placed at the average height of the birds in the centre of each section. The mean of the temperatures at these locations was considered to be the ambient temperature of the barn. The manufacturers claim that the bare thermistor time constant is 10 seconds while that for the thermistors used in this study was of the order of 25 seconds. The time constants for the barns were of the order of 10 minutes and, therefore, justified the 4-minute interval readings taken in this study.

To evaluate the degree of temperature stratification, dry-bulb temperatures were measured at a lower and an upper level across the centre of the building. In both barns, the lower level corresponded to the bird level, the upper level being approximately 800 mm from the ceiling. Thermistors were placed also at the top and bottom of the centre fan to measure the vertical temperature gradients across the fan openings.

The measured ambient dewpoints were checked by recording the wet-bulb temperature at the centre of each barn. The wet-bulb sensor consisted of a thermistor embedded in a moistened wick located in a 100-mm diameter plexiglass tube and aspirated by a 12-volt, 75-mm diameter fan. A bag filter was placed over the end of the tube to minimize dust entering the tube and soiling the sensor. The filter was serviced prior to each monitoring period. A further check on the dry-bulb temperatures and dewpoints was provided by hand-held instruments. One such instrument was a humidity and temperature tester (MIK-2000, Novasina AG, Zurich, Switzerland) which was specified as being accurate to 0.7°C and 2 percent relative humidity over a temperature range of -10°C to +50°C. This instrument was provided with a series of salt solutions to calibrate the instrument before use. Another instrument used in this study was a digital psychrometer (90023-C, Atkins Technical Inc., Gainesville, Florida). This instrument measured the wet-bulb depression and was specified as being accurate to 0.1°C over a range of -20 to 100°C. All these instruments were read to within 0.1°C of each other and confirmed the rated accuracy of the thermistors.

4.2.1 Energy Data Acquisition System

The major component of the barn energy balance is the heat loss due to ventilation and, consequently, the accurate measurement of ventilation rate was of critical importance in this study. Therefore, insulated discharge ducts were constructed downstream from each exhaust fan to determine the ventilation rates in each of the two barns.

The duct size was 0.6 m x 0.6 m x 3.7 m long in each instance, incorporating an air straightener to assist in stabilizing the air flow. Jorgenson (1983) suggested a duct length of 11.5 times the duct diameter and the point of measurement at least 5 times the diameter from the location of the straightener. In this study, the straightener was 3.0 m from where the air-flow readings were taken but, for practical reasons such as transportation and labor requirements, the duct length was less than the recommended length. The shrouds were removed from the operating fans in Barn B during the monitoring period and were reattached at the completion of the study.

A thermistor anemometer (Model TA3000, Airflow Developments, Buckinghamshire, England) was used to measure the air-flow rates from the exhaust fans, twice during each 24-hour monitoring period. These readings were checked with a hot-wire anemometer (Sierra Instruments, Redlands, California). According to the manufacturers, the thermistor anemometer was accurate to within 2 percent of reading over a temperature range of -20 to +60°C. Both anemometers were calibrated in an air velocity calibrator located in the Department of Mechanical Engineering, University of Alberta. This was accomplished by introducing a regulated air flow from a compressor into a chamber followed by an orifice plate. Various air flows were obtained by varying the pressure differential between the chamber and room, that is, across the orifice plate, as measured by a Validyne pressure transducer (Sierra Instruments, California). The anemometer probes were both directionally sensitive. During calibration they were aligned with the airstream from the nozzle at the nozzle centreline with the probe body at 90° to the nozzle centreline and 12mm downstream of the nozzle. The anemometers measured air velocities that read to within 0.3 m/s of each other throughout the study.

The discharge ducts were swept clean prior to each monitoring period. A traverse of 25 locations in each duct cross-section was used to measure the exhaust air velocities. The resultant flow rates were the product of the duct areas and the mean air velocities. Additional air flow measurements were taken during windy conditions. Fan speed was monitored by mounting magnetically-activated electronic switches on the operating fan housing. These switches used the Hall Effect for sensing the magnetic field generated by a magnet secured to the rotating fan shaft. The pulses obtained were converted into a dc voltage by using a frequency-to-voltage conversion circuit. This output voltage was proportional to fan speed. The "Hall" circuit was calibrated under field conditions by using a strobo-tachometer (Model 30-K, Pioneer Electric and Research Corp., Illinois). The output dc voltages from the sensors in Barn B indicated whether each two-speed fan was operating at high or low speed or not at all. For the variable-speed fans in Barn A, the shaft speeds were adjusted manually throughout their range and the corresponding output voltages and air-flow rates measured simultaneously. From these data, a linear function was developed to relate the air-flow rate to the output voltage or speed of the fan. A thermistor also was located in the fan ducting downstream of each fan in Barn A to determine the fan on/off state.

Ventilation rates were further checked by employing a tracer gas, sulphur hexafluoride (SF_6), and an ion-capture detector chromatograph (AI Industrial, Cambridge, England). This method was utilized for the slowly-running, variable speed fans of Barn A only, using the fan-duct, constant flow procedure described by Leonard et al. (1984a). Supply lines were extended from the mobile laboratory to each fan discharge duct and were situated immediately upstream from the fan. The SF_6 sample line was located near the end of the duct and samples, taken on a 25-point grid across the duct section, were distributed to the detector chromatograph in the mobile laboratory. This was calibrated against a certified gas mixture (Matheson Gas Products, Canada) which was guaranteed to have a concentration of 0.33 ppm plus or minus 0.015 ppm. The zero gas used was the ambient outside air. The ventilation air removed by each fan was calculated from the ratio of the injection rate to the resultant downstream concentration. This method assumed complete mixing of the air in the duct. The air-flow rates measured by this method varied by up to 10 percent from the readings obtained from the thermistor anemometer. The anemometer readings were used in this study as incomplete mixing was evident in the fan ducting due to insufficient duct length and to injection of SF_6 at a single point.

Several factors influenced the effectiveness of the fans in exhausting the contaminated ambient air. The main causes for varying fan capacities, during the course of the study, were the size of inlet opening, the position of the inlets with respect to wind direction, and/or the number of fans in operation. These factors would influence the negative pressure differential across the barn and, hence, fan performance. The fans in Barn A generally were running at a very low speed. During the second run, the variable speed controllers were not set for the same ambient temperatures, resulting in fan 1 moving air at a lower rate than fans 2 and 3. The fans in Barn B were operated in stages as the chickens matured. During the first run, only one fan was in operation while, by run 5, four fans were operating at maximum delivery during the daytime. As the birds matured, their metabolic activity increased, their heat requirements decreased, and the outdoor temperatures increased, thus requiring a substantial increase in the air exchange rate.

The air exhausted by the fans contains both sensible and latent heat. Sensible heat also was lost by conduction through the structural components. Heat-flux plates, as described by DeShazer et al. (1982), were used to measure the conductive heat losses from each barn. These were positioned on a representative location of each structural component of the building, that is, walls, floor, and ceiling. These locations were determined by scanning each component with an infrared pyrometer (Omega Engineering, Stamford, Conn.) and obtaining a surface temperature that was representative of that structure. The manufacturers claimed that the pyrometer was accurate to within 0.1°C of reading. However, this instrument was not calibrated but was used to provide a qualitative and approximate indication of a suitable heat-flux plate location.

The heat flows measured by the heat-flux plates were checked by a heat-flow meter (Concept Engineering, Old Saybrook, Conn.). This heat-flow meter also was used as the standard in the calibration of the individual heat-flux plates, where the heat flow was expressed as a function of the temperature differential across the heat-flux plates. This was accomplished by placing the heat-flux and heat-flow plates on a heated copper plate and comparing the temperature differentials across the heat plates. The copper plate has an uniform thermal flux due to its high thermal conductivity and any error associated with placing the heat-flux plates on the building materials was insignificant. According to the manufacturers, this meter was accurate to within 1 percent of reading over a temperature range of -30 to 1100°C and was confirmed by the calibration results. The heat-flux plates were placed on the inside surfaces of the building rather than the outside surfaces to exclude the solar radiation component on the plates. These conductive heat losses also were checked by using the temperature data and the known thermal characteristics of the building components. These losses were calculated by multiplying the building exposure factors by the temperature differential between barn and outside air and by the number of birds. The measured conductive heat losses were found to vary by only 4 percent from these calculated losses.

The floor heat loss from the upper story of Barn A was negligible, since the lower portion of the barn was maintained at approximately the same temperature. This was confirmed with pyrometer and heat-flow measurements. In Barn B, the surface temperature and the heat fluxes of the floor were checked with the pyrometer and the heat-flow meter, respectively. The conductive heat losses through the attached walls in both barns also were negligible due to the small temperature differential across the walls.

Supplemental heat input in each barn was calculated using the water temperature differential between the inlet and outlet and water flow-rate measurements. Thermistors were placed on the inlet and outlet pipes inside the barn and wrapped in thermal insulation in order to measure the temperature differential between the inlet and outlet. The effect of thermal mass of the heating system was considered in this study in determining the energy dissipated by the heating pipes to the pullet environment but, due to the short length of pipes used, was insignificant. The flow rate of heating water within these pipes was measured with an ultrasonic Doppler flow-meter (Polysonics Flowmeter, Houston, Tx.) which utilized the Doppler principle as its basis for operation. The transducer was attached, over 20 diameters clear of constrictions, to the clean surface of the pipe and a crystal emitted an ultrasonic pulse into the waterflow. The resultant change in frequency was detected by the transducer and converted to a signal proportional to the water velocity. This meter was calibrated previously against a magnetohydrodynamic flow-meter (Type 1803 SANS-CA, Foxborough Co. Ltd., Le Salle, Que.) and was found to be linear (Appendix A).

In Barn B, thermistors were placed directly over the brooders to indicate if the brooders were on or off, during the first monitoring period. The heating capacity of these brooders were determined by attaching a commercial gas meter (Branchard Engineering Ltd., Edmonton, Alta.) on-line and obtaining the energy content of the gas from the local supplier. This meter was not calibrated but any error associated with the brooder heat input was regarded as insignificant due to its minor contribution to the total supplemental heat input.

All the pertinent parameters that were related directly to the heat and moisture balance have been described. However, other parameters that were related indirectly to the building energy balance also were monitored. Water consumption rates were measured daily by a water meter (Neptune Meters, Toronto, Ont.), while pressure differential was measured by a low-range, variable-reluctance, differential pressure transducer (Validyne, Model DP45, Sierra Instruments, Cal.) along with a carrier demodulator unit (CD15 Universal Transducer Indicator, Validyne Engineering Corp.). A dc voltage was obtained from this unit that was proportional to the differential pressure. Measurements were taken at the centre of both units. This pressure transducer was calibrated before each monitoring period using an inclined manometer attached to the equipment rack and gave a linear output of 0.39 V/mm H_2O.

Attic temperature was measured by placing a thermistor in a representative location in the attic, usually at mid-height, to assess the heat loss through the ceiling and the heat gain through solar heating of this air space. This representative location was determined from hand-held temperature readings (MIK-2000, Novasina AG, Zurich, Switzerland). The attic temperature was used to calculate the temperature differential between the attic air and both the ambient and outside air and, consequently, the conductive heat loss through the ceiling.

4.2.2 Air Quality Measurements

The NH_3 and CO_2 concentrations were monitored at mid-height in the centre of both end sections. Concentrations of H_2S were monitored in the centre of each barn. To determine the production rates of NH_3 and CO_2, the concentrations of these gases also were measured at the exhaust fan locations.

Air samples were drawn from each location within the barn through the heated conduit, as aforementioned, to the mobile laboratory. A programmed automatic sampler (Feddes and McQuitty, 1977) was used to sequentially draw an air sample from each sampling location and distribute it to each of the analyzers used to measure the dewpoint and the concentrations of the gases. A schematic diagram of the gas sampling and measurement system is shown in Figure A2 (Appendix A). Solenoid-activated valves were located on each sampling line and were sequenced by the data logger. A separate line and pump was connected to the dust sampler to sample dust concentrations. For both barns, an additional sampling line sampled outside air to provide background concentrations of CO_2 and to provide a continuous check of the zero of the NH_3 analyzer.

The analyzers used in this study to measure NH_3 and CO_2 concentrations were of the non-dispersive infrared gas type (Model 315 A, Beckman, Fullerton, Cal.) while H_2S concentrations were measured by a sulphur analyzer (Melroy Laboratories, Springfield, Virginia) which utilized the flame photometric detection process. Before each monitoring period, certified calibration gases (Matheson Gas Products, Canada) were utilized to set the zero and span of these analyzers. The analyzers were spanned with the calibration gases which were specified by the manufacturers to be accurate to within 2 percent of reading. The manufacturers of the gas analyzers also supplied regression equations relating voltage output with concentrations of NH_3 (linear) and CO_2 (polynomial), as shown in Appendix A, which were verified by hand-held Draeger tube readings.

Atmospheric dust concentrations were monitored for 15 minutes of each hour of each run, in the centre of each replacement pullet unit, approximately at bird level. These air samples were drawn through an iso-kinetic probe to ensure uniform sampling of particle sizes and distributed to a photometric particle counter (Climet Instrumentation, Redlands, Cal.) housed in the mobile laboratory. This instrument counted the particles at 3-minute intervals and allocated them to five size ranges, that is, greater than 0.5, 1.0, 2.0, 5.0, and 10μm. Honey and McQuitty (1976) and Curtis (1981) suggested that the particles less than 5μm were most likely to be detrimental to the health of birds and operator. Consequently, these counts were grouped into the two size ranges of less than 5μm and greater than 5μm.

A summary of the primary sensors, their locations, and scanning rate, for each of the two barns monitored are given in Table 4.2. Each of the two barns was monitored over

Table 4.2 A SUMMARY OF THE PRIMARY SENSORS, THEIR LOCATIONS AND SCANNING RATE, FOR EACH OF THE TWO BARNS MONITORED.

Sensor type and sampling rate Location		Number of locations Barn A On-floor	 Barn B Cages
Thermistors:			
20-minute readings:			
outside		1	1
attic		1	1
inlet		-	3
high level		3	4
low level		9	8
wet-bulb		1	1
	Total:	15	18
Heat-flux plates:			
20-minute readings:			
ceiling		1	1
floor		-	1
walls		4	4
	Total:	5	6
Thermistors:			
4-minute readings:			
downstream from fan		3	-
hot water		2	2
	Total:	5	2
Sequential air sampling:			
30-minute readings:			
dewpoint, ammonia, carbon dioxide, hydrogen sulphide[1]			
exhaust		3	4
ambient		2	2
outside		1	1
Pressure differential:			
4-minute readings:		1	1
Dust:			
Sequential particle size counts:		1	1
Fan rpm:			
4-minute readings:		3	4
Water consumption: daily readings:		1	1
Doppler flow meter: each run:		1	1

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[1] Daily readings of hydrogen sulphide, 20-minute recording (manual)

a complete 24-hour period at 3 to 4-week intervals for one complete 18 to 20-week production cycle. All the sensors, extension wire, and sampling tubing were installed permanently into each barn for this period. In addition, the location of the sensors was determined by convenience and protection from the operator and birds. The mobile laboratory was moved to a new site after each monitoring period and this was facilitated by the use of multi-pin connectors and fittings which enabled the fast uncoupling of extension wires and tubing. The monitoring dates and operating data summary for Barns A and B are given in Tables 4.3 and 4.4, respectively.

4.3 Data Recording and Processing

The conditioned output signals from each instrument were processed by a micro-processor controlled data logger located in the mobile laboratory and converted into a digital format. The data logger can accomodate up to 144 input signals, namely, 32 general analog and 112 dedicated thermistor inputs. A manually-adjusted time clock was set to scan these signals.

Output from the data logger was recorded on a paper-tape punch throughout each monitoring period. After each run the paper tapes were read at the Computing Services Centre, University of Alberta, by a paper-tape reader which transformed the digital data into raw voltage values. Using a computer program developed within the Department of

Table 4.3 SUMMARY OF OPERATING DATA DURING EXPERIMENTAL RUNS FOR BARN A (ON-FLOOR UNIT).

Run Number	1	2	3	4	5
Run date	Sep 23	Oct 18	Nov 14	Dec 13	Jan 10
Start time, hours	1620	1300	1300	1600	1200
Number of birds	5752	5733	2447	2397	2365
Age of birds, days	10	36	61	90	118
Last date of barn cleaning	September 11, 1983				
Feeders on, hours	0700, 0745, 0900, 1000, 1130, 1345, 1530				

Table 4.4 SUMMARY OF OPERATING DATA DURING EXPERIMENTAL RUNS FOR BARN B (CAGE UNIT).

Run Number	1	2	3	4	5	6
Run date	Dec 5	Jan 3	Jan 31	Mar 1	Mar 21	Apr 11
Start time, hours	1402	1100	1100	1200	1300	1300
Number of birds	13776	13668	13643	13616	13596	13580
Age of birds, days	6	35	63	93	113	134
Last date of barn cleaning	Nov 28	Nov 28	Jan 24	Jan 24	Mar 21	Mar 21
Feeders on, hours	0830, 1430					

Agricultural Engineering, the data were converted into the proper units of the variables being measured and hourly averages were obtained. From these data, each component of building heat balance was calculated and tabulated. Dust data were recorded automatically and separately on paper tape and were read into a computer file after each run.

The data also were plotted on a Tektronix 4051 graphics terminal and Tektronix 4662 plotter via the Michigan Terminal System and Fortran plotting software supported by the University of Alberta Computing Services. Backup copies of the data were placed on magnetic tape for storage. Appendix A is a listing of the pertinent equations in the Fortran program that were used to convert the raw voltage data to engineering units, including schematic diagrams of some of the instrumentation used, while Appendix B illustrates a sample output data file.

4.4 Energy Balance

The barn energy balance comprised conductive heat losses, ventilation sensible and latent heat losses, supplemental heat gains, the bird sensible and latent heat gains, and the conversion of sensible to latent heat within the building.

The conductive heat losses were calculated from the combined thermal resistances of the structural materials, as aforementioned. Standard psychrometric equations (ASHRAE,

1981) were used in the Fortran program to calculate the enthalpies, specific volumes, and specific humidities of the inlet and exhaust air in both barns. The ventilation rates were calculated as stated and, subsequently, the amount of sensible and latent heat added to the air when passing through the barns was determined. A separate program was necessary for each barn due to the different number of analog and thermistor sensors used.

The supplemental heat gain was calculated from the hot-water flow and the temperature differential between the inlet and the outlet. In addition, the heat input from the brooders in Barn B was calculated from the flow rate and energy content of the natural gas, as aforementioned. The remaining function in the energy balance was the bird heat gain. This was calculated by subtracting the supplemental heat input from the sum of conductive and ventilation heat losses. Ventilation latent heat loss was calculated from the difference in inside and outside humidity ratios, the specific volume of dry air, and the ventilation rate. In turn, ventilated sensible heat was found by deducting the ventilated latent heat from the total ventilated heat. Some of the bird's sensible heat input may have been used to evaporate water from the litter/droppings. The extent to which this may have occurred was determined from the literature as described later. The equations used in the above energy balance are given in Appendix C while an error analysis of the data are presented in Appendix D.

5. RESULTS AND DISCUSSION

A lack of data pertaining to the heat and moisture production of replacement pullets within confinement units and to the air quality within these facilities was the fundamental reason for this study. Rates of bird heat and moisture production were obtained by performing an energy balance on the two barns monitored. Air quality within these two barns was established by sampling representative locations with regard to air contaminants.

The total heat losses in this study were considered to be those due to air exchange or ventilation and the conductive heat flow through the structural components of the building. These losses were balanced by the total heat gains which consisted of the supplemental heating system and the total heat output from the birds. Since the heat losses and the supplemental heat gain were measured, the unknown term or the heat output of the birds could be determined. This term also represented other sources of heat losses and gains such as those associated with lights, motors, moisture evaporation from the litter, and heat generation within the litter. These sources were considered to be negligible and incorporated into known heat gains. The entire unknown term was assumed to be the total heat output of the birds.

5.1 Temperature and Relative Humidity

Figure 5.1 shows the mean hourly exhaust, high, low, attic, and outside dry-bulb temperatures in Barn A with 36-day old replacement pullets. The ventilation system provided reasonable control of the building thermal environment, as shown in Figure 5.1, by allowing less variation in the barn temperature than that exhibited by the outside temperature. Figure 5.1 also illustrates the vertical stratification of temperature that occurred when measured 1.5 m (high) and 0.5 m (low) above floor level. This indicated some lack of air mixing within this barn. The mean difference in temperature between the high and low levels was 1.5°C, with the temperature being lower at the lower level. In addition, some incomplete air mixing was evident in that the mean exhaust temperatures were 1°C greater than those of the ambient barn air (Table 5.1).

Also of interest was the mean deviation in temperature between the attic and outside air. The maximum mean difference for Barn A was 3.5°C during the fourth monitoring period, while the mean differences throughout the production cycle was 2°C (Table 5.1). Similarly, the mean difference in attic and ambient temperatures for the on-floor unit was 18°C, being greater when outside temperatures were at a minimum. These data indicated that the insulation was effective in controlling the conductive heat loss through the ceiling.

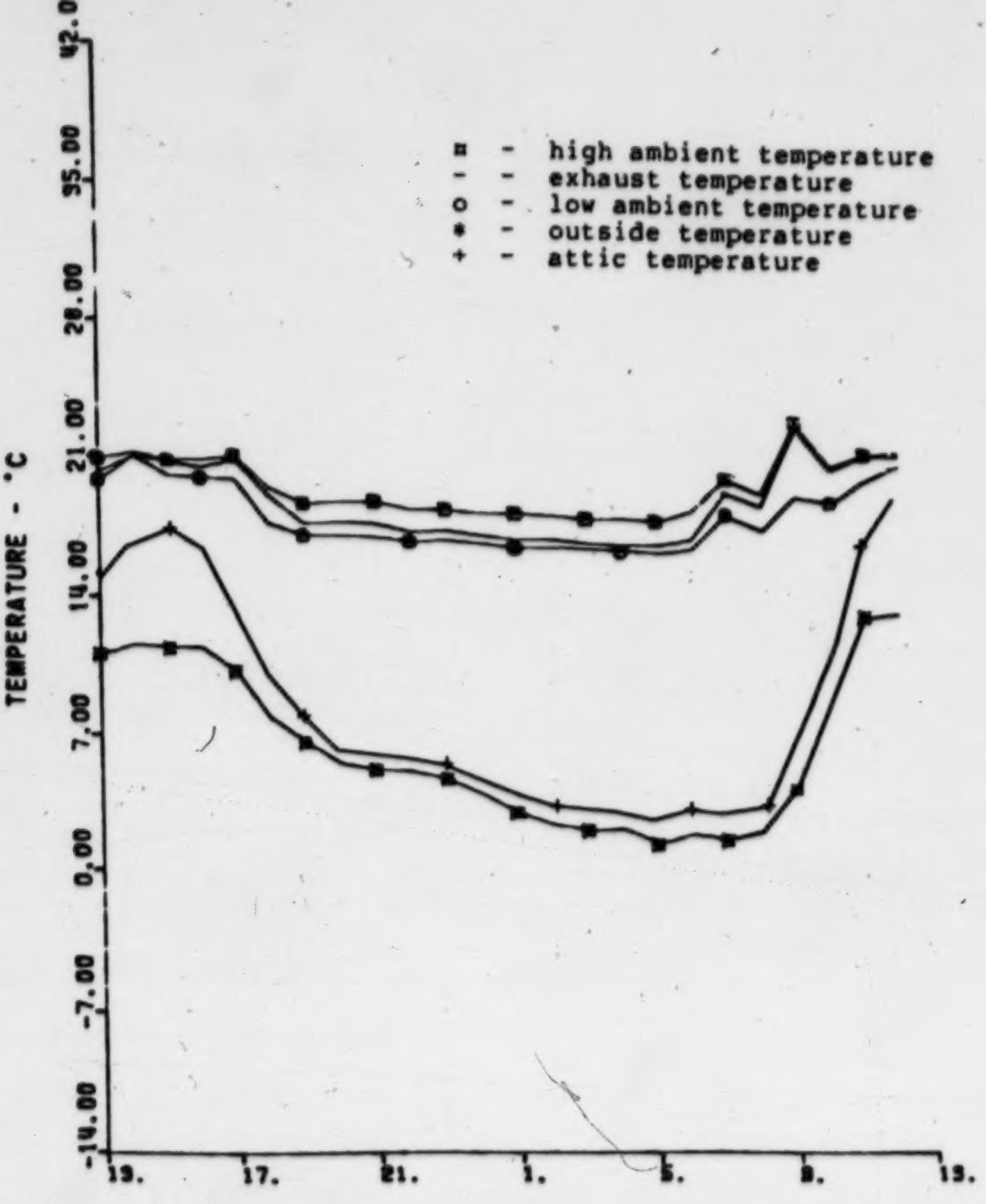


Figure 5.1 Mean hourly exhaust, high, low, attic, and outside dry-bulb temperatures in Barn A with 36-day old replacement pullets.

Table 5.1 SUMMARY OF AIR CONDITIONS FOR BARN A - MEAN MEASURED VALUES.

Run Number	1	2	3	4	5
Ambient Relative humidity, %	36.5	53.7	59.6	51.4	63.8
(range)	(28/45)	(35/68)	(50/78)	(33/75)	(56/79)
Temperature,°C: ambient	28.5	18.3	17.2	15.4	10.5
(range)	(26/32)	(17/21)	(15/20)	(14/19)	(7/14)
exhaust	29.6	18.7	17.9	16.6	11.3
(range)	(26/33)	(16/22)	(15/21)	(14/20)	(7/15)
outside	11.7	6.2	0.4	-19.4	-10.2
(range)	(6/19)	(1/13)	(-2/4)	(-14/-23)	(-8/-12)
high level	29.6	19.4	18.1	16.7	11.0
(range)	(26/33)	(17/23)	(16/21)	(14/20)	(7/14)
low level	28.2	17.9	16.8	14.9	10.3
(range)	(25/32)	(16/21)	(14/20)	(13/18)	(6/14)
attic	13.8	8.3	1.6	-15.9	-8.3
(range)	(7/24)	(2/20)	(-1/8)	(-11/-20)	(-6/-10)

Figure 5.2 shows the mean hourly exhaust, high, low, attic and outside dry-bulb temperatures in Barn B with 35-day old replacement pullets. This figure is similar to Figure 5.1 in that vertical temperature stratification was evident between 1.8 m (high) and 0.9 m (low) above floor level within this unit, while the mean exhaust temperatures were approximately 1°C greater than those of the ambient barn air. The mean temperature gradient between the upper and lower level was less than 1°C (Table 5.2) suggesting that the air distribution was slightly more uniform in this barn than in Barn A.

The mean attic temperature in Barn B had an overall mean value of 1.7°C higher than the mean outside temperature and 17.8°C less than the mean ambient temperature. The greatest differences occurred during the first week of the production cycle when outside temperatures were at a minimum (Table 5.2). These results suggest, as in Barn A, that the ceiling insulation was effective in restricting the heat flow. Extremes of outside temperature also were observed; from -23°C to +19°C and from -9°C to +13°C for Barns A and B, respectively. A mean vertical air temperature gradient of 1°C and 4°C existed between the top and bottom measuring locations at the exhaust fans in Barns A and B, respectively, with the air temperature being higher at the top of the fan than that at the bottom for both barns.

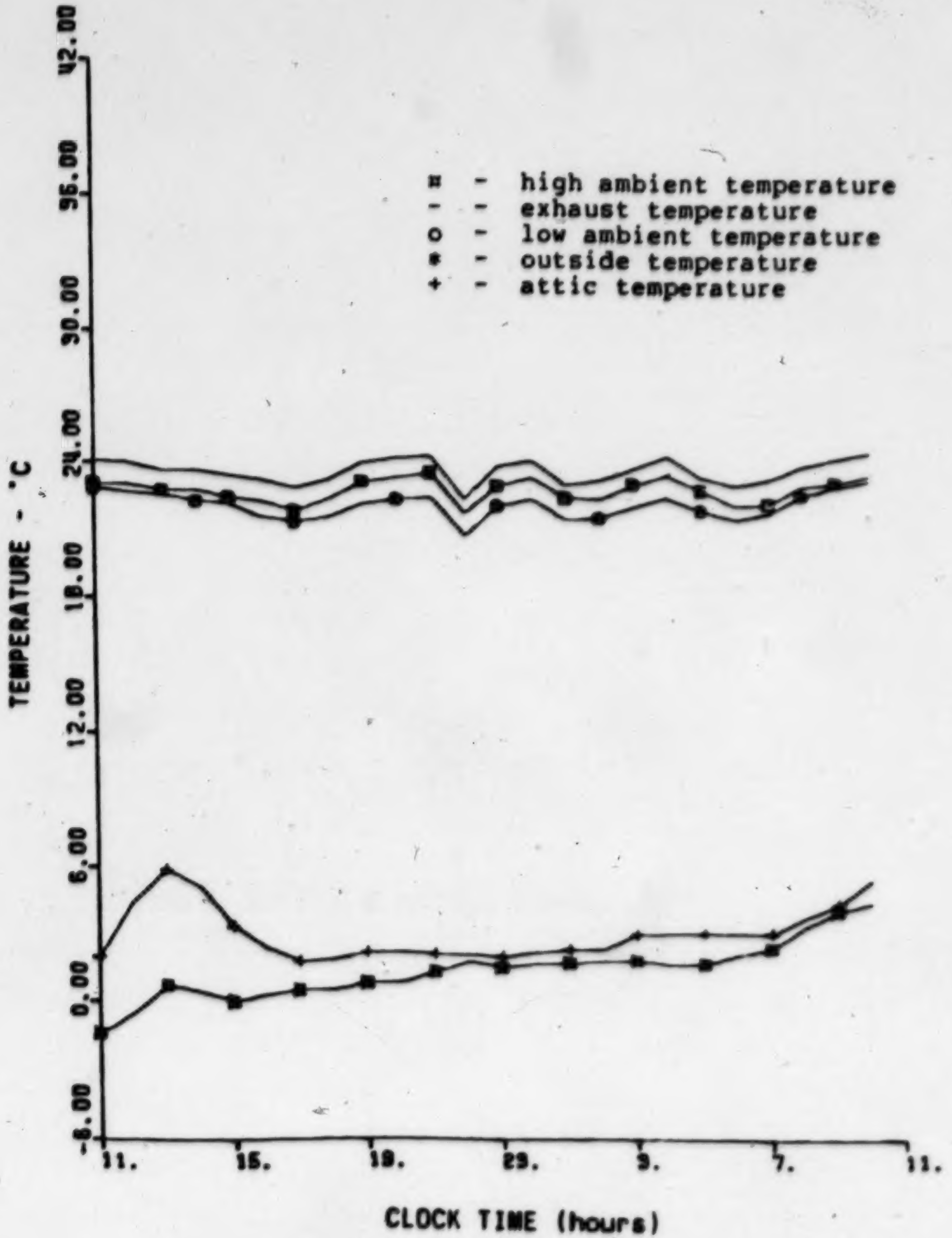


Figure 5.2 Mean hourly exhaust, high, low, attic, and outside dry-bulb temperatures in Barn B with 35-day old replacement pullets.

Table 5.2 SUMMARY OF AIR CONDITIONS FOR BARN B - MEAN MEASURED VALUES.

Run Number	1	2	3	4	5	6
Ambient Relative humidity, %	43.0	46.0	41.0	45.6	47.9	38.7
(range)	(32/65)	(34/56)	(26/63)	(28/67)	(28/67)	(18/58)
Temperature, °C: ambient	24.4	22.4	20.3	17.1	16.4	18.6
(range)	(23/26)	(21/24)	(18/23)	(15/20)	(14/23)	(13/25)
exhaust	27.2	23.6	21.2	17.2	17.4	18.7
(range)	(25/29)	(22/25)	(18/24)	(15/20)	(15/23)	(14/25)
outside	-6.8	1.4	2.2	-0.3	2.1	4.7
(range)	(-9/-4)	(-1/5)	(-1/7)	(-2/3)	(-1/9)	(-3/13)
high level	24.4	22.7	19.9	16.6	16.9	19.2
(range)	(23/26)	(22/24)	(17/23)	(15/20)	(15/23)	(19/25)
low level	24.2	22.0	19.8	16.3	16.4	18.3
(range)	(23/25)	(21/23)	(17/23)	(15/19)	(14/23)	(14/25)
attic	-4.6	3.1	3.9	1.4	3.2	6.7
(range)	(-4/-9)	(-1/5)	(-1/7)	(-2/3)	(-1/9)	(-3/13)

The ambient temperature in both barns was controlled at 30-32°C when the chicks were introduced at the start of the rearing cycle. Over the 18 to 20-week period, the inside ambient temperature was decreased gradually to approximately 11 and 18°C for Barns A and B, respectively. The Hy-Line W-77 Commercial Management Guide (1982) recommended, with respect to the pullets in Barn A, a temperature of 30-32°C at bird level at the start of the rearing cycle and a reduction of 3°C per week until 21°C was reached. Similarly, the Shaver S288 Commercial Management Guide (1982) recommended, with respect to the pullets in Barn B, an initial temperature of 28-31°C and a reduction of 3°C each week, until a minimum of 15°C was reached.

Therefore, the ambient temperatures in Barn A were below the recommended values after the first week of production (Table 5.1), suggesting that the replacement pullets may have had to increase their food intake to maintain thermoneutral conditions. Conversely, the ambient temperatures in Barn B were below the recommended value during the first week and above the suggested minimum values for the remainder of the rearing cycle (Table 5.2). The mean ambient temperature ranged from 7 to 32°C and from 13 to 26°C throughout the monitoring period for Barns A and B, respectively. Management technique appeared to be very poor in Barn A resulting in the wide variation in ambient temperature over the rearing cycle.

Lighting plays an important role in poultry production and, therefore, the data were analyzed further in terms of light and dark periods. Table 5.3 gives the overall mean air temperatures measured in both barns during night and day periods. The mean ambient temperature difference between light and dark periods was 2.7 and 2.6°C for Barns A and B, respectively, with the temperature, as expected, being higher during the day than at night (Table 5.3). There was a negligible difference in temperature between the high and low (bird) levels for the corresponding light and dark periods in both barns. The mean exhaust temperature difference between light and dark periods measured was 2.9 and 2.2°C for Barns A and B, respectively (Table 5.3).

The recommended inside relative humidities for pullet facilities are a minimum of 50 percent and a maximum of 75 percent (Canadian Code for Farm Buildings, 1977; ASAE, 1984). The measured relative humidities for Barns A and B are shown in Tables 5.1 and 5.2, respectively. These data were found to have a mean value of 53.0 (range: 36.5 to 63.8) percent for Barn A and 43.7 (range: 38.7 to 47.9) percent for Barn B. Therefore, the amount of moisture in the ambient air in Barn B was, for every run, below the minimum recommended levels, suggesting that the barn was somewhat overventilated. In this regard, a reduction in ventilation rates would have resulted in a decrease in total heat loss due to ventilation and a lower supplemental heating

Table 5.3 SUMMARY OF EXPERIMENTAL DATA FOR AIR TEMPERATURES DURING DAY AND NIGHT PERIODS - OVERALL MEAN MEASURED VALUES.

BARN	A		B	
Period	Day	Night	Day	Night
Temperature, °C:				
Ambient	19.4	16.7	21.1	18.5
High level[1]	20.4	17.7	21.3	18.8
Low level[2]	19.1	16.4	20.9	18.3
Exhaust	20.4	17.5	22.1	19.9
Attic	1.5	-1.6	4.9	0.1
Outside	-1.2	-3.2	2.1	-0.1

[1] 1.5 m and 1.8 m above floor level, respectively
[2] 0.5 m and 0.9 m above floor level, respectively

requirement, but at the expense of a decrease in air quality.

The relative humidities measured in Barn A were above the minimum recommmended values throughout the rearing cycle, except for the first run. The mean hourly relative humidity values over each trial run in Barn A showed less variation than the values between runs. The mean measured values in Barn B showed little variation from run to run over the rearing cycle.

5.2 Fan Performance and Pressure Differential

Fan performance data and pressure differentials for both barns throughout the monitoring period are given in Table 5.4. The three variable-speed fans in Barn A were operating mainly at low speeds throughout the production cycle. In Barn B, only one, two-speed fan was in operation during the first week of the rearing cycle, but all four were required during the last two monitoring periods due to increased bird heat production and higher outside temperatures. The mean high and low deliveries for the fans in the cage unit were approximately 1700 and 700 L/s, respectively. The fans in Barn A operated within a range of 40 to 650 L/s throughout the monitoring period.

Figures 5.3 and 5.4 illustrate the mean hourly ventilation rates over a 24-hour monitoring period for Barns A and B, respectively. Figure 5.3 shows that the ventilation rates remained relatively constant in Barn A at 0.04

Table 5.4 FAN PERFORMANCE DATA AND PRESSURE DIFFERENTIAL FOR THE TWO BARNS.

	Fan output, L/s				Pressure differential, mm water
	1	2	3	4	
BARN A: RUN					
1	79	69	100	-	0.7
	(73/85)[1]	(67/73)	(98/103)	-	
2	51	248	252	-	1.3
	(0/126)	(60/602)	(78/650)	-	
3	81	102	118	-	0.7
	(76/86)	(98/107)	(116/121)	-	
4	84	73	70	-	0.5
	(70/90)	(68/89)	(67/40)	-	
5	93	43	67	-	0.4
	(89/98)	(40/44)	(65/68)	-	
BARN B: RUN					
1	-	-	621	-	3.2
	-	-	(200/770)	-	
2	420	-	803	-	0.1
	(150/750)[2]	-	(760/830)	-	
3	1062	-	662	842	0.3
	(650/1650)	-	(610/700)	(830/1420)	
4	873	1637	772	929	0.2
	(660/1650)	(1630/1640)	(700/1320)	(730/1610)	
5	895	1640	1050	1266	0.5
	(400/1650)	(1630/1645)	(680/1630)	(710/1620)	
6	991	1754	1291	1725	0.6
	(100/1700)	(1740/1760)	(410/1760)	(1720/1730)	

[1] variable-speed fan operating range

[2] approximate two-speed fan volumes

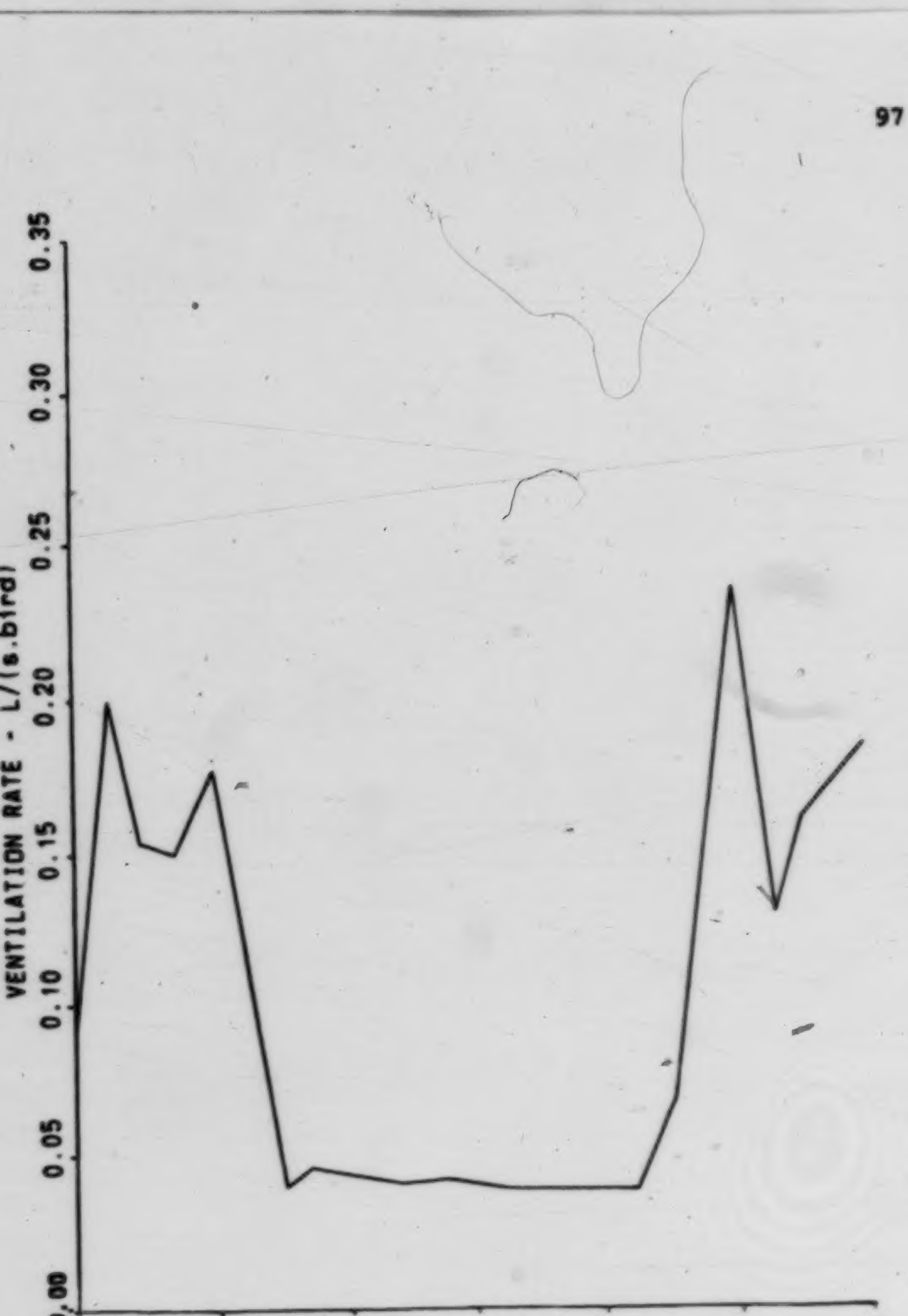


Figure 5.3 Mean hourly ventilation rates in Barn A with 36-day old replacement pullets.

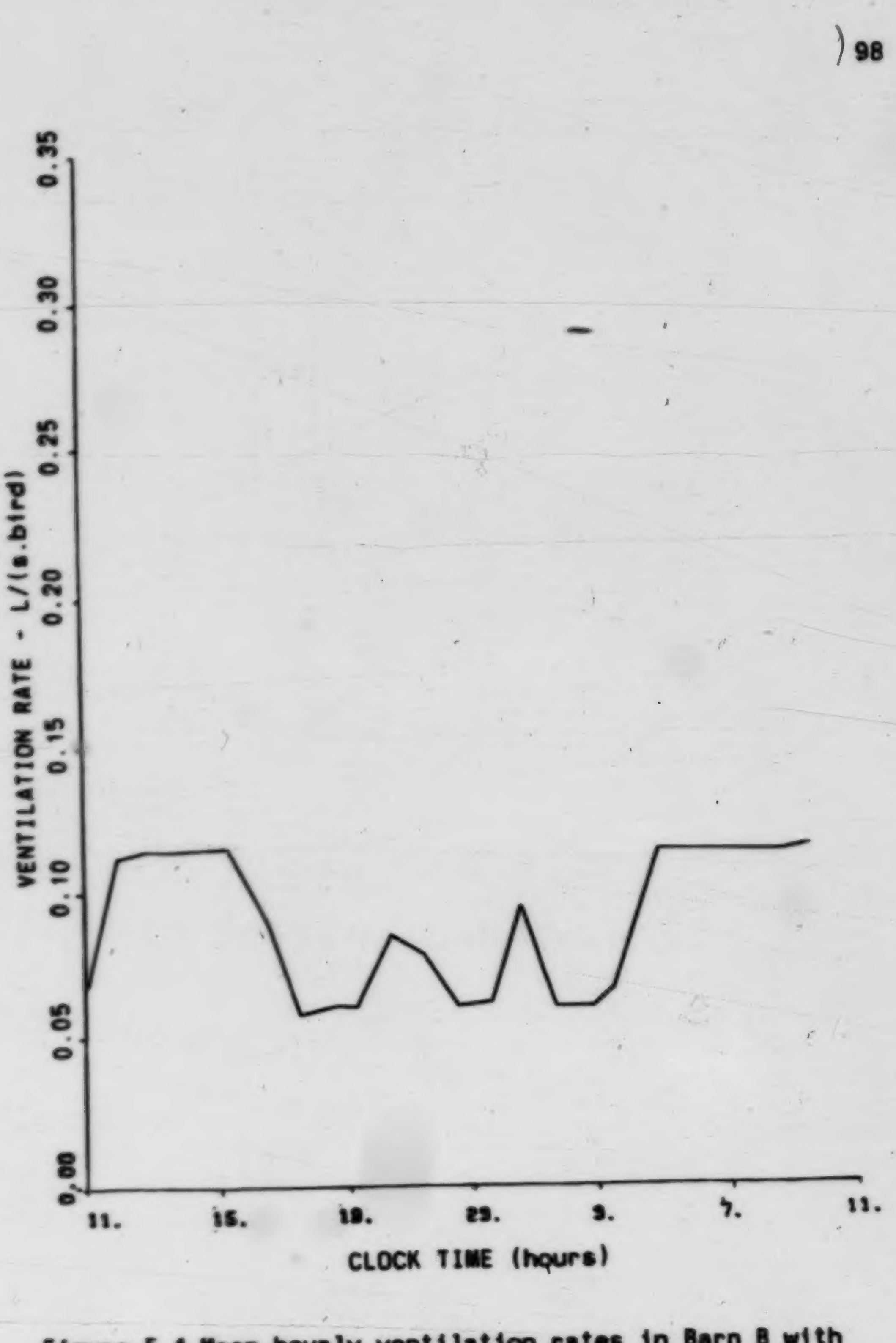


Figure 5.4 Mean hourly ventilation rates in Barn B with 35-day old replacement pullets.

L/(s.bird) during the night while exhibiting fluctuations during the day. The high rates shown during the day were considered to be the result of increased bird activity during this period. These trends were not as apparent in Barn B, as shown in Figure 5.4. The ventilation rates in Barn B exhibited wider variations during the night and smaller fluctuations during the day than those in Barn A for this monitoring period. Feeding times (Table 4.4) also were reflected in this figure. The reason for the peaks during the night in this facility was not apparent. They may be explained, in part, by some external disturbance, such as the barking of the guard dogs frightening the birds but this was not monitored in this study.

The mean ventilation rates (L/(s.bird)) within each run are tabulated in Table 5.5. These data illustrated that ventilation rates may differ widely between replacement pullet units. In Barn A, the mean ventilation rates increased with bird age and, hence, with bird total heat production, reaching a maximum of 0.12 L/(s.bird) during the third run. These ventilation rates then decreased due to the extremely cold outside temperatures (Table 5.1). In Barn B, there was a gradual increase in ventilation rates as the birds matured, ranging from an initial value of 0.05 L/(s.bird) to a maximum of 0.42 L/(s.bird) at the end of the production cycle. Under winter conditions, and at 80 percent relative humidity, Winchell (1982) recommended ventilation

TABLE 5.5 DAILY MEAN VENTILATION AND HEAT BALANCE DATA FOR EACH RUN DURING THE PULLET PRODUCTION CYCLES IN BARNS A AND B.

Bird age, days	Vent rate L/s	Ventilation heat loss kJ/h	Building heat loss kJ/h	Supplemental heat input kJ/h	Bird total heat input kJ/h	Vent/ total heat loss
	per bird					
BARN A:						
10	0.04	4.7	0.7	3.0	2.4	0.88
36	0.10	7.2	0.5	1.0	6.7	0.92
61	0.12	14.1	1.4	1.2	14.3	0.91
90	0.10	18.9	3.1	2.4	19.6	0.86
118	0.09	11.4	1.9	-	13.3	0.86
BARN B:						
6	0.05	8.6	2.1	8.4	2.3	0.80
35	0.09	11.7	1.6	-	13.3	0.88
63	0.19	17.8	1.4	-	19.2	0.93
93	0.33	26.0	1.2	-	27.2	0.96
113	0.36	26.6	1.1	-	27.7	0.96
134	0.42	29.4	1.1	-	30.5	0.96

rates of 0.02 and 0.19 L/(s.bird) for 2-week old and 8 to 20-week old pullets, respectively. Therefore, the air exchange rates found in this study exceeded the recommended values throughout, except for the latter half of the rearing cycle in Barn A. These high rates were reflected in the low relative humidities found in both barns.

A minimum static pressure differential of 1.3 mm water gauge (w.g.) is recommended for negative pressure systems (Turnbull and Bird, 1981; Munroe et al., 1982). Varying pressure differentials were evident in both barns, ranging from 0.4 to 1.3 mm w.g. and from 0.1 to 3.2 mm w.g. for Barns A and B, respectively (Table 5.4). Therefore, the fans in both barns were operating against a pressure differential below the minimum recommended values during each run, except for run 2 in Barn A and the first run in Barn B. The mean pressure differential was approximately the same for both barns throughout the rearing cycle, that is, 0.8 mm w.g. Low pressure differentials are indicative of inadequate air velocities, and, in turn, inadequate air mixing within a barn. The values recorded substantiate the earlier comments with respect to temperature gradients found in both barns, that is, air mixing was incomplete in each instance.

5.3 Heat Balances

Typical hourly heat losses from, and gains to, the pullet environment during a 24-hour monitoring period are given in Figures 5.5 and 5.6 for Barns A and B, respectively. As shown by these figures, the diurnal fluctuations in the total heat productions were very considerable. The hourly heat production values were less during the dark than during the light periods. The main reasons for the hourly fluctuations were considered to be due to the on/off operation of the exhaust fans causing heat to be removed or stored at higher rates than it was being produced and changes in the activity levels of the birds. A drastic change in bird activity was observed when the feeders were activated (Tables 4.3 and 4.4) and when the producer checked the birds and equipment, being most noticeable in Barn A.

Figures 5.5 and 5.6 also illustrate the high proportion of the total heat loss that is removed by the ventilation system. The contributions of the conductive heat loss and the supplemental heat gain remained relatively constant for this monitoring period for both barns, except for the sudden increase in supplemental heating during the morning period (Figure 5.5) in Barn A. This extra heating was required to balance the sudden increase in ventilation heat loss so that a constant thermal environment was maintained. Bird activity increased and, in turn, temperature increased resulting in this sudden increase in ventilation heat loss. These peaks correspond to the peaks in ventilation rate as shown in Figure 5.3 due to

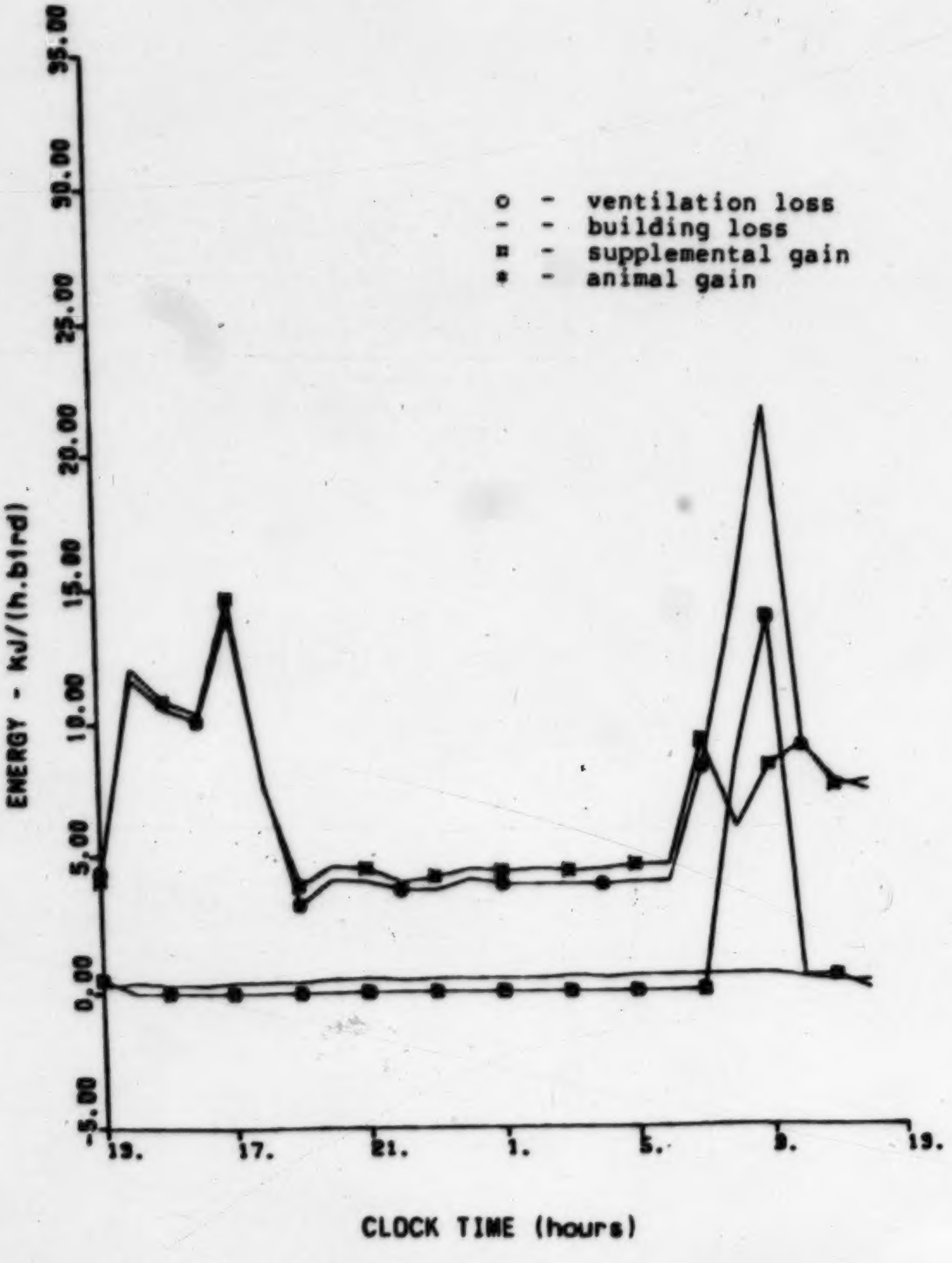


Figure 5.5 Mean hourly ventilation, building, supplemental and animal components of the heat balance in Barn A with 36-day old replacement pullets.

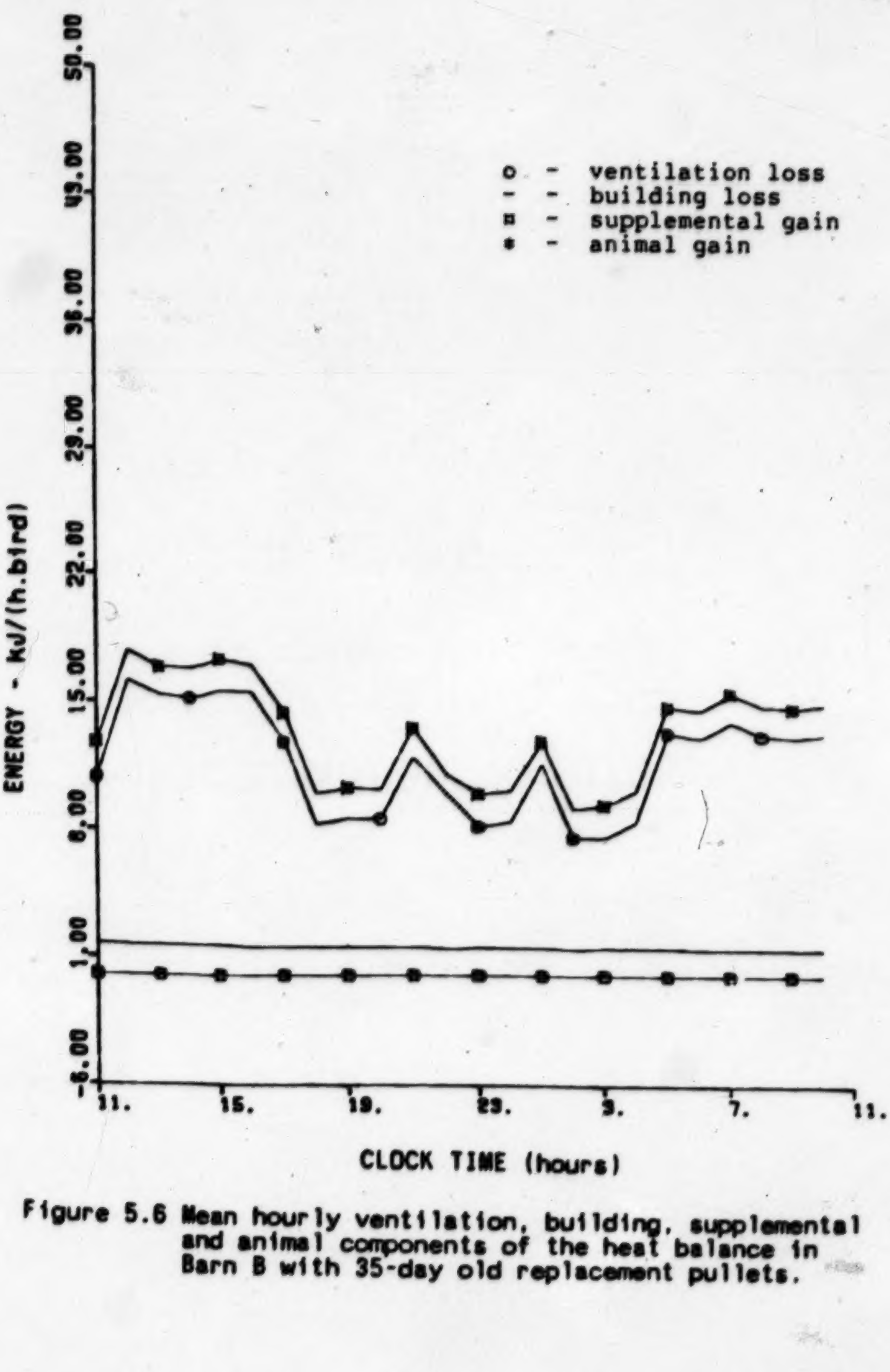


Figure 5.6 Mean hourly ventilation, building, supplemental and animal components of the heat balance in Barn B with 35-day old replacement pullets.

increased bird activity at feeding time.

The daily mean values for each run over the full production cycles for ventilation rates, and heat losses and gains are tabulated in Table 5.5 for both barns. The ventilation heat loss ranged from 4.7 to 18.9 kJ/(h.bird) and from 8.6 to 29.4 kJ/(h.bird), with mean values of 11.2 and 20.0 kJ/(h.bird), for Barns A (2-90 days) and B (2-134 days), respectively. The ventilation heat loss increased gradually with bird age for both barns (except run 5 in Barn A), with the heat loss being higher in the cage facility than that in the on-floor unit (Table 5.5). As noted for Figures 5.5 and 5.6, the ventilation heat loss consisted mainly of the bird total heat production in both barns except for the first run in each instance when the supplemental heat load was the major contributor.

The heat loss by conduction remained approximately constant during the rearing cycle for both barns with values ranging from 0.5 to 3.1 kJ/(h.bird) (2-90 days) and from 1.1 to 2.1 kJ/(h.bird) (2-134 days) for Barns A and B, respectively (Table 5.5). These values suggest that the thermal insulation was effective in minimizing the heat flow through the structural components due to the temperature differential between the ambient or barn air and the outside air.

As previously discussed, supplemental heating was required to overcome the heat deficit within the building when the total heat produced by the birds alone was insufficient to balance the total heat loss. Accordingly, supplemental heating was required in Barn B for the first week of production only while, in Barn A, supplemental heating was required (range: 1.0 to 3.0 kJ/(h.bird)) for up to 14 weeks due to colder outside temperatures. The highest supplemental heat requirement was 8.4 kJ/(h.bird), in Barn B, when the birds were in their first week of the growth cycle (Table 5.5) and when their total heat production was at a minimum. The heat produced in Barn B by the birds after the first week was sufficient to maintain a comfortable thermal environment within the barn. The replacement pullets in Barn A increased their total heat production with age, thereby reducing supplemental heat requirements. However, the supplemental heat requirements increased during the fourth monitoring period when outside temperatures were at a minimum (Table 5.1).

All of the heat balance components were measured except for the bird total heat gain. This value was calculated by subtracting the supplemental heat input from the total heat loss (sum of ventilation heat loss and conductive heat loss). The bird total heat production values for both barns are shown in Figure 5.7 and tabulated in Table 5.5.

The daily total heat production rates varied from 2.4 to 19.6 kJ/(h.bird) (2-90 days) and from 2.3 to 30.5 kJ/(h.bird) (2-134 days) for Barns A and B, respectively. There are no published data available on total heat

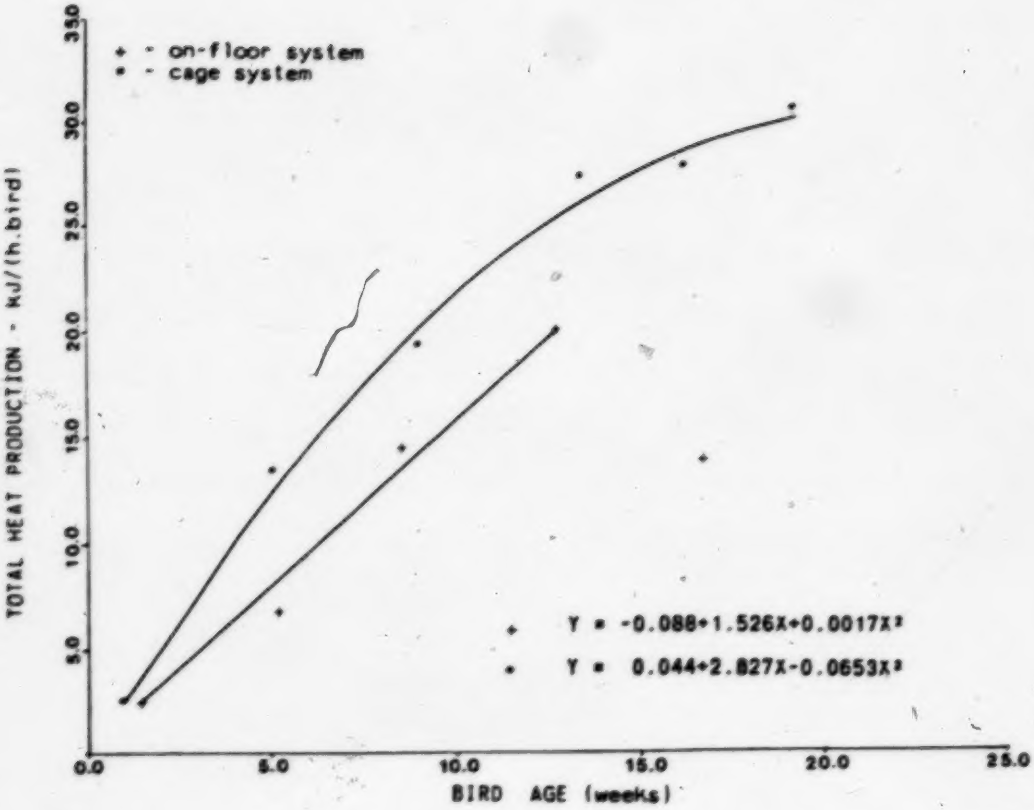


Figure 5.7 Total heat production of replacement pullets in Barns A and B during complete production cycles.

production rates for replacement pullets with which to compare these results. However, data have been reported on both calorimetric and commercial studies in relation to the heat and moisture loads of broilers and laying hens. The birds used in each of these studies were of different ages and different strains and, consequently, a comparison was carried out on the basis of bird bodyweight.

In addition, management type may have affected these data. Hence, a comparison of values obtained in this study for the on-floor unit was undertaken with those obtained in broiler studies while the data for the cage-reared pullets were compared with data from layer studies. The mean weight of the pullets was not measured in this study and, consequently, target weights given in the Commercial Management Guides (1982) were used. These data are presented in Appendix E. These weights were checked constantly by the operator in Barn B but not in Barn A.

Feddes et al. (1984b) reported mean total heat production rates, for White Leghorn-type layers, of 19.8 kJ/(h.kg) using a mean bird age of 332 days. These values were measured, under winter conditions, at an ambient barn temperature of 15.1°C with birds exposed to over 14 hours of light per day. The total heat production rates for the pullets, in Barn B, at the end of the rearing cycle (134 days) were higher (24.4 kJ/(h.kg)) than these reported values. In other studies cited by Feddes et al. (1984b), mean heat production rates reported for layers by Ota and

McNally (1961), DeShazer et al. (1969), DeShazer et al. (1970), Olson et al. (1974), and Riskowski et al. (1977) were 21.2, 18.0, 20.5, 22.2, and 20.7 kJ/(h.kg), respectively. The values found in this study for Barn B ranged from 30.7 to 24.4 kJ/(h.kg) from 2 to 134 days, respectively with a mean value of 28.3 kJ/(h.kg). Expressed on a bodyweight basis, heat production rates decreased as the pullets grew older, that is, as the birds increased in weight. Thus, the data obtained in Barn B for the pullets would appear to be in line with those reported for mature layers of similar type, as shown in the figure relating total heat production on a bodyweight basis with bird age in days (Appendix F).

Feddes et al. (1984a) also measured total heat production rates for broilers under commercial conditions. They reported total heat values ranging from 40.3 to 62.1 kJ/(h.kg) at a mean ambient temperature of 25.6°C. Other studies on heat production rates for broilers were reported by different researchers but the results were presented on a bird basis and the studies were undertaken at various periods of the production cycle. These results are presented here on a bodyweight basis for 44-day old broilers. This age period was common to all the studies and at the latter stages of the broiler production cycle. The production rates at 44 days cited by Longhouse et al. (1968), Deaton et al. (1969), Denbow and Kuenzel (1981), ASAE Yearbook (1984), Feddes et al. (1984a), and in Barn A were 30.3, 30.7, 24.8, 39.2, 45.2, and 23.0 kJ/(h.kg), respectively. The difference in these data may be explained, in part, by the difference within bird type, feed intake, stocking densities, and ambient conditions with a resultant variation in total heat production. The values found in this study for Barn A ranged from 32.4 to 19.0 kJ/(h.bird) (2-90 days) with a mean value of 24.3 kJ/(h.bird).

Figure 5.7 illustrates the best-fit curves relating bird total heat production with bird age for the on-floor and the cage facilities. These curves were obtained by using a Tektronix statistical package available in the Department of Agricultural Engineering, University of Alberta. The last data point for Barn A (Figure 5.7) was omitted from these curves as the value was uncharacteristically low due to the malfunction in the feed auger and the resultant disruption in feed supply for that monitoring period. A repeat of this run was not possible because the operator removed the pullets to the layer cages later that day.

Equations for the data curves in Figure 5.7 were developed to relate bird total heat production with bird age. The correlation coefficient between the two variables for both barns were considered to be high ($R^2 = 0.99$). The equations for Barn A and Barn B, respectively, are as follows:

$$Y = -0.088 + 1.526X + 0.0017X^2 \qquad (3)$$

and

$$Y = 0.044 + 2.827X - 0.0653X^2 \qquad (4)$$

where Y = total heat production per bird, kJ/(h.bird), and

X = age of birds, weeks.

A typical growth curve for White Leghorn-type pullets relating bird weight with bird age is illustrated in the Agricultural Engineers Yearbook (1984) and a best-fit equation relating these two variables ($R^2 = 0.99$) was derived as:

$$W = -0.062 + 0.0912X - 0.00103X^2 \qquad (5)$$

where W = bird weight, kg, and

X = age of birds, weeks.

Equation 5 is a second degree polynomial equation similar to those presented in equations 3 and 4 which was expected since heat production and growth are related.

The ratio of heat loss by ventilation to the total heat loss from the building over the rearing cycle ranged from 0.86 to 0.92 (mean: 0.89) for Barn A (2-90 days) and from 0.80 to 0.96 (mean: 0.92) for Barn B (2-134 days). The high ratios indicated the minor proportion of total heat loss from the replacement pullet environment through the building shell (Table 5.5).

The overall mean heat gains and losses for the dark and light periods during each run are given in Table 5.6. The production rates for night and day periods are presented here as light affects bird activity which in turn influences metabolic rate and bird total heat production.

Table 5.6 SUMMARY OF HEAT BALANCE DATA DURING DAY AND NIGHT FOR THE TWO BARNS - OVERALL MEAN MEASURED VALUES.

BARN	A		B	
PERIOD	Day	Night	Day	Night
Ventilation heat loss, kJ/(h.bird)	12.5	10.1	23.5	17.2
(range)	(4/20)	(4/18)	(10/33)	(7/28)
Building heat loss, kJ/(h.bird)	1.5	1.4	1.5	1.4
Bird total heat gain, kJ/(h.bird)	11.8	9.9	23.5	17.2
(range)	(2/21)	(3/18)	(4/34)	(1/29)
Percentage reduction, day to night, %	16		27	
Supplemental heat, kJ/(h.bird)	2.2	1.6	1.5	1.4
Vent heat loss /total heat loss	0.90	0.88	0.94	0.92

Similarly, equations were developed relating total heat production with bird age for the corresponding light and dark periods in both barns. The correlation coefficients for the light and dark periods of Barns A and B also were considered to be high ($R^2 = 0.99, 0.95, 0.98, 0.99$, respectively). The equations are as follows:

Barn A -

Day: $Y = -1.1304 + 2.1569X - 0.0325X^2$ (6)

Night: $Y = 0.7567 + 0.9970X + 0.0309X^2$ (7)

Barn B -

Day: $Y = -0.1785 + 3.7744X - 0.03254X^2$ (8)

Night: $Y = 0.2486 + 2.0334X - 0.0302X^2$ (9)

The total heat production rates for the replacement pullets in Barn A ranged from 1.8 to 21.3 and from 2.9 to 18.2 kJ/(h.bird) (2-90 days) for the light and dark periods, respectively (Table 5.6). The corresponding rates for Barn B ranged from 3.6 to 32.3 and from 1.2 to 29.0 kJ/(h.bird) (2-134 days) during the light and dark periods, respectively. These data gave an overall mean reduction in bird total heat production from day to night of 16 and 27 percent for Barns A and B, respectively. This reduction can be attributed to the fact that birds are sitting or inactive at night, as observed by DeShazer et al. (1970), cited by Scott et al. (1983). They reported that the heat loss from chickens is 20 to 40 percent lower in a sitting as compared to a standing position. The difference in reduction between the two barns may be, in part, due to the lower heat production in Barn A than in Barn B and to the fact that birds in on-floor units have a greater capability to huddle together than those confined in cages.

The mean reduction of 27 percent found in Barn B compared reasonably well with the data of Riskowski et al. (1977) who reported a reduction of 22 percent for layers on a 14-hour lighting schedule. Feddes et al. (1984b) found a mean reduction of 17 percent for caged layers under winter conditions. Bird densities, lighting schedule, and feed intake were different in all the above data. A summary of the mean bird total heat production data measured during day and night, for the two barns, for each monitoring period is given in Appendix G.

The overall mean supplemental heat requirements for both barns showed little variation during the dark and light periods (Table 5.6) with the heating demand being greater during the day than during the night, especially in Barn A. There also was very little variation between light and dark periods in the overall mean conductive heat losses in both barns. These values were 1.5 and 1.4 kJ/(h.bird), respectively (Table 5.4), suggesting that the building insulation was effective in restraining the outward heat flow through the structure. In addition, the ratio of heat loss by ventilation to total heat loss was higher during the light period (0.90 and 0.94) than during the dark period

(0.88 and 0.92) for Barns A and B, respectively. The total ventilation heat losses also were higher in Barn B than in Barn A, with overall mean values of 23.5 and 17.2 kJ/(h.bird) and of 12.5 and 10.1 kJ/(h.bird) for the day and night periods, respectively.

5.4 Moisture Balances

The amount of moisture removed by ventilation comprised the total moisture released by the birds through respiration, and by evaporation from the litter/stored droppings and from wet surface areas. Hourly values of moisture production for Barns A and B are shown in Figures 5.8 and 5.9. The fluctuations occurring in moisture production, as shown in these figures, are considered to be due to changes in ventilation rates (Figures 5.3 and 5.4). During the night, production rates in Barn A remained relatively constant (Figure 5.8) for this run, while the daytime production rates exhibited greater variation, possibly due to the litter being moved or disturbed by the daytime activity of the pullets. The production rates in Barn B showed more variation during the night (Figure 5.9) for this monitoring period than those in Barn A. These fluctuations were similar to variations in the ventilation rates for this run (Figure 5.4).

The daily mean moisture production rates ranged from 0.7 to 2.2 g/(h.bird) (2-90 days), and from 1.1 to 4.1 g/(h.bird) (2-134 days) for Barns A and B, respectively

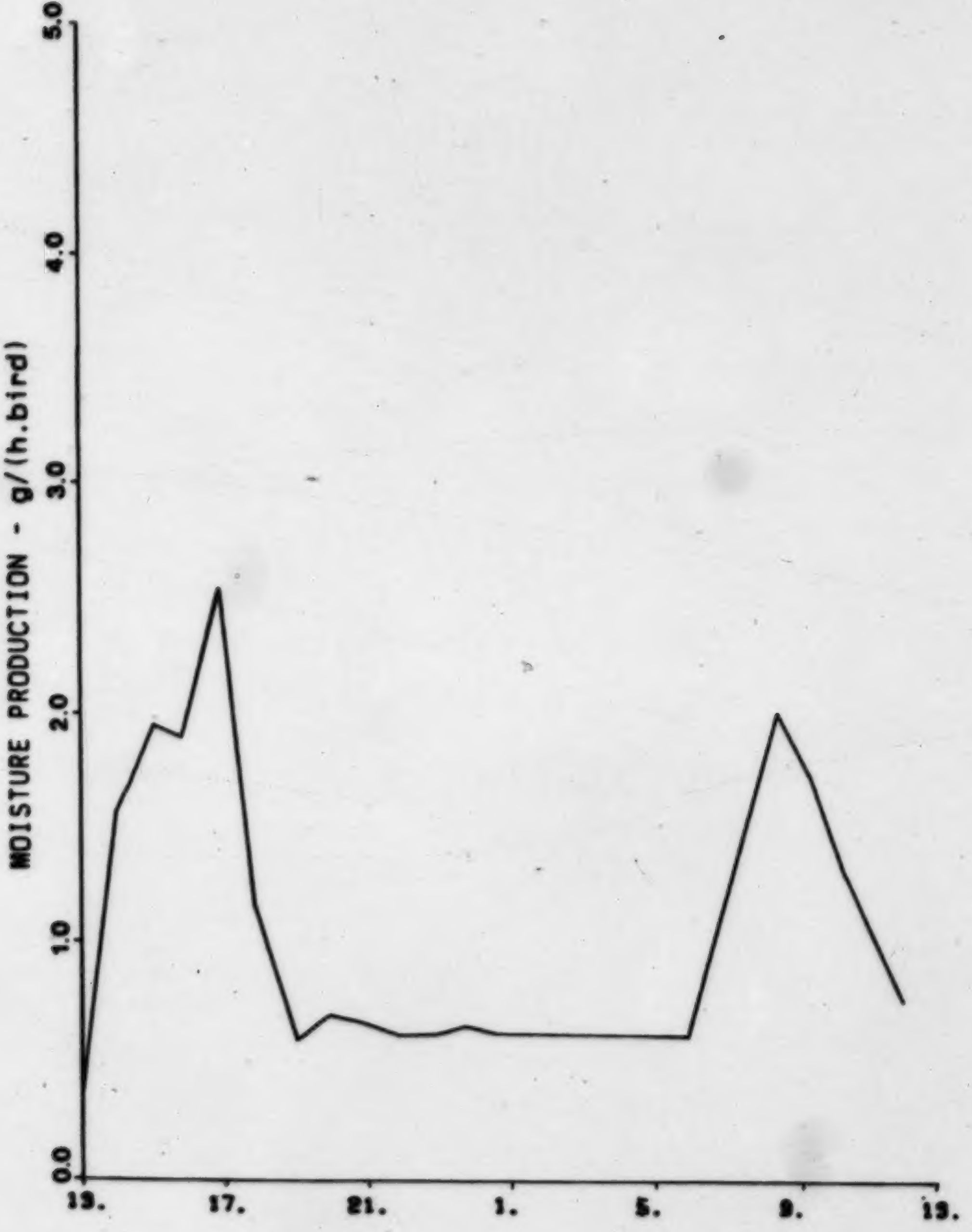


Figure 5.8 Mean hourly moisture removal rates by ventilation in Barn A with 36-day old replacement pullets.

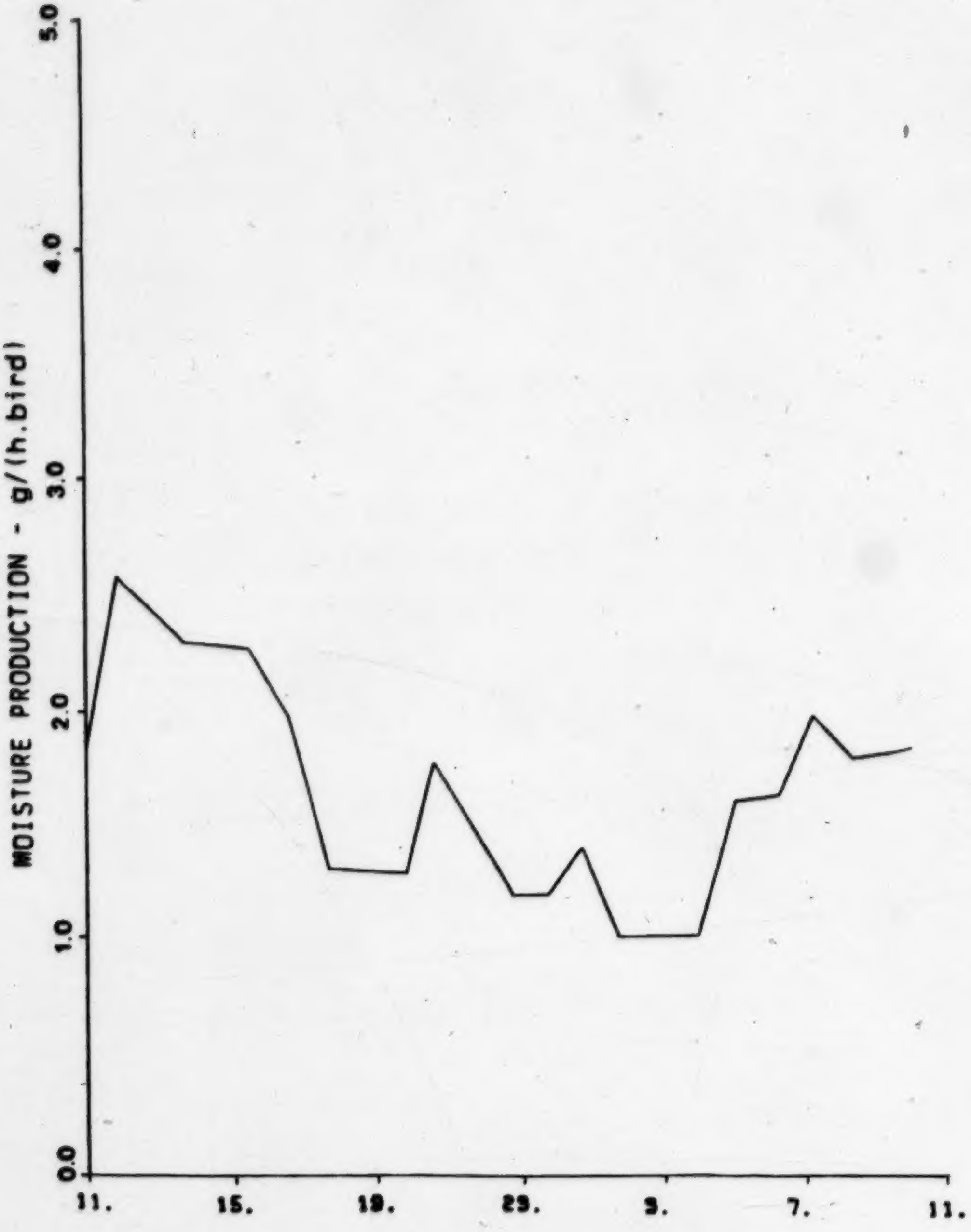


Figure 5.9 Mean hourly moisture removal rates by ventilation in Barn B with 35-day old replacement pullets.

Table 5.7 DAILY AVERAGE MOISTURE PRODUCTION VALUES FOR EACH RUN DURING THE PULLET PRODUCTION CYCLES IN BARNS A AND BARN B.

Bird age, days	Moisture production g/(h.bird)	Water used mL/(h.bird)	Moisture production /water used %	Vent latent /total vent %
BARN A:				
10	0.7	0.2[1]	350	36.2
36	1.1	2.3	48	39.2
61	2.2	2.1	105	39.3
90	2.1	1.7	124	27.7
BARN B:				
6	1.1	1.3[3]	85	34.0
35	1.7	3.1	55	36.7
63	2.3	18.0[2]	13	31.9
93	2.7	7.0	39	25.8
113	2.8	6.5	43	25.9
134	4.1	9.8	42	34.4

[1] Medication offered during monitoring

[2] Leakage over floors during monitoring

[3] Medication not offered during monitoring

(Table 5.7). Production rates were higher in Barn B than in Barn A due to the droppings management and lower relative humidity present in the latter. The moisture production rates in the on-floor unit remained relatively constant (2.1 g/(h.bird)) after the pullets were removed to the lower level of the building while production rates in the cage facility increased with bird age and, hence, with bird size.

For comparison, as stated in relation to heat production, with other data the moisture production rates were expressed on a bodyweight basis. Feddes et al. (1984a) reported production rates ranging from 12.3 to 7.2 g/(h.kg) (5-44 days) for broilers under winter conditions. The corresponding rates, at 44 days, found in this study was interpolated to 3.9 g/(h.kg) for Barn A. Accordingly, moisture production rates for 44-day old broilers cited by Longhouse et al. (1968), Deaton et al. (1969), and Feddes et al. (1984a) were 4.3, 6.1, and 9.2 g/(h.kg). Moisture production rates found in Barn A were 4.7 (range: 9.5 to 2.0) g/(h.kg). The differences in bird type, feed intake, stocking densities, and ambient conditions in broiler units with those found in pullet facilities influenced the variations in the results.

Similarly, moisture production rates for layers cited by DeShazer et al. (1969), Olson et al. (1974), Riskowski et al. (1977), Feddes et al. (1984b), and for pullets in Barn B were 2.3, 2.2, 1.7, 2.0, and 5.1

g/(h.kg), respectively. The high mean values found in this study for Barn B were due to the high production rate during the first run (14.7 g/(h.kg)) when the birds were of little weight. If the value for this run were eliminated, the mean value was 3.2 g/(h.kg).

The average moisture production data and the ratio of ventilation latent to total heat loss for both barns over the production cycle are tabulated in Table 5.7. The moisture loads in Barns A and B differed, with production being higher in Barn B than in Barn A, following a similar trend to total heat production. Equations were developed, as with heat production, to relate moisture production in each rearing barn to bird age. A high correlation was found to exist between these two variables ($R^2 = 0.90$ and 0.94, respectively). The equations that best fit these data for Barns A and B, respectively, are plotted in Figure 5.10 and are as follows:

$$Y = 0.223 + 0.283X - 0.0102X^2 \qquad (10)$$

and

$$Y = 1.139 + 0.075X + 0.0034X^2 \qquad (11)$$

where Y = moisture production rate, g/(h.bird), and

X = age of the birds, weeks.

The moisture production rate for the final monitoring period in Barn A has been omitted from the above equation (10) due to the aforementioned reasons of feed supply failure and a subsequent reduction in evaporative heat loss which accompanyed the low ambient temperatures

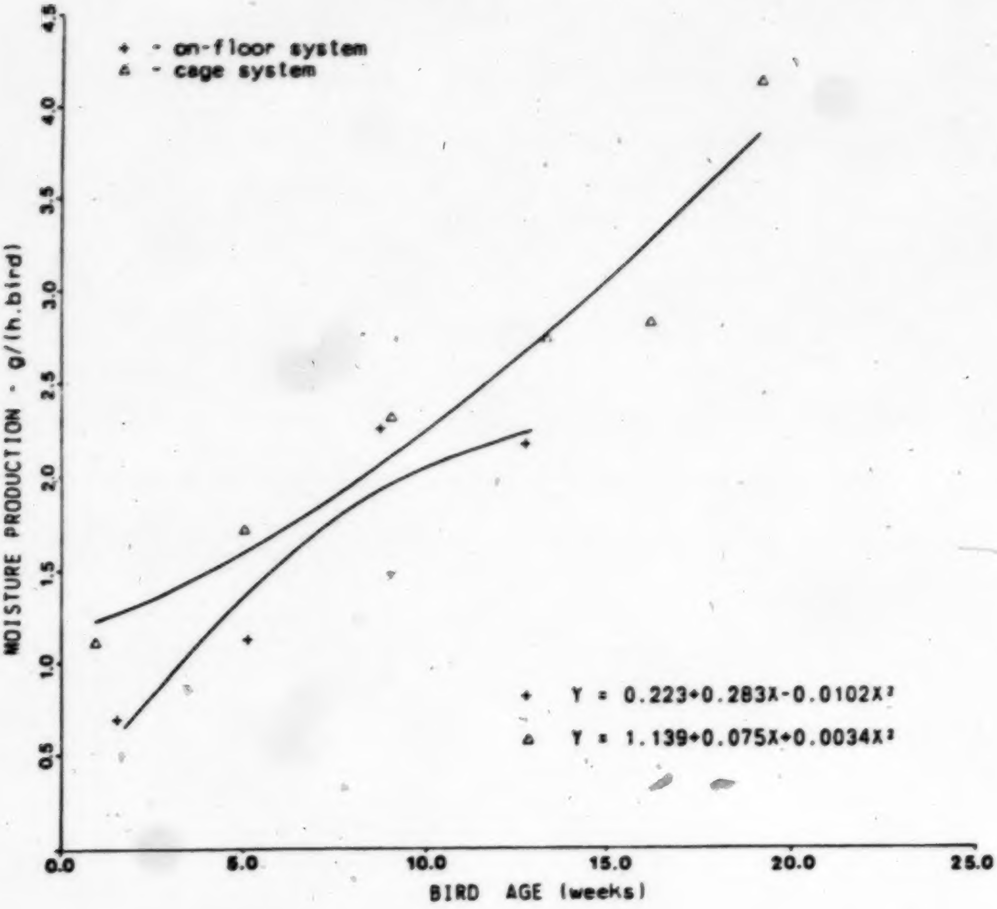


Figure 5.10 Total moisture production of replacement pullets in Barns A and B during complete production cycles.

for this run. Although Feddes et al. (1984a) found the best-fit curve to be a third-degree polynomial, equation 10 presented here for the on-floor unit had the highest R^2 value and was consistent with the heat and CO_2 production curves and with the growth curve.

Similarly, equations were developed relating moisture production rates with bird age for light and dark periods for both barns:

Barn A -

Day: $Y = -0.0298 + 0.4236X - 0.01916X^2$ (12)

Night: $Y = 0.4012 + 0.1522X - 0.00192X^2$ (13)

Barn B -

Day: $Y = 1.2705 + 0.1524X + 0.0022X^2$ (14)

Night: $Y = 1.0448 + 0.0044X + 0.0045X^2$ (15)

In addition, a high correlation existed between moisture production and bird age for the above equations (R^2 = 0.98, 0.83, 0.95, 0.90, respectively).

The installed water meter measured the amount of water that was supplied to the barn. However, all of this water was not consumed by the pullets as some was spilled on the litter/droppings due to leakages or clumsiness, or was evaporated into the air. Therefore, the quantity of water supplied was termed "water use". Water use rates ranged from 0.2 to 2.6 g/(h.bird) (2-90 days) and from 1.3 to 9.8 g/(h.bird) (2-134 days) for Barns A and B, respectively, throughout the production cycle. The third set of data collected from Barn B showed an unusually high value of water usage (Table 5.7). This value was due to the fact that some drinking cups were forced open by the producer to add water to the droppings. This practice facilitated easier droppings removal from the barn.

The percentage of the water used that was removed by the ventilation system ranged from 39 to 85 (mean: 53) percent in Barn B (Table 5.7). Feddes et al. (1984b) noted that, in layer barns, water production was not similar to water usage, with a mean value of 37 percent. The corresponding values for Barn A ranged from 48 to 124 percent. The high values for the last two runs in Barn A (Table 5.7) suggested that more moisture was vented than was used. This may be explained, in part, by the litter acting as a source for moisture, that is, the litter was becoming dry due to a greater loss of water from the litter than was being added. This observation also was cited by Feddes et al. (1984a) for broiler barns, a mean ratio of 77 percent being reported.

The ratio of latent heat removed by ventilation to the total heat removed remained relatively constant for both barns. These values ranged from 0.28 to 0.39 and from 0.26 to 0.37 for Barns A and B, respectively, the means being 0.36 and 0.32, respectively (Table 5.7). Thus, approximately two thirds of the total heat loss by ventilation was in sensible heat form.

The amount of moisture produced by the pullets also was investigated in terms of lighting schedule, on the same basis as in heat production. The overall mean moisture production data during night and day for the two barns are given in Table 5.8. The mean moisture production rates measured were 1.65 and 3.22 g/(h.bird) during the light period, and 1.34 and 1.77 g/(h.bird) during the dark period for Barns A (2-90 days) and B (2-134 days), respectively. As before, comparisons were made on a bodyweight basis. Moisture production values cited by Riskowski et al. (1977) and Feddes et al. (1984b) for layers during the day were 1.9 and 2.2 g/(h.kg) and during the night 1.5 and 1.7 g/(h.kg), respectively. The corresponding values in Barn B were 3.5 and 1.9 g/(h.kg), respectively.

The overall mean reduction in moisture production rates from day to night were 19 and 45 percent for Barns A and B, respectively. Feddes et al. (1984b) noted in three cage layer barns a mean reduction in moisture production from day to night of 25 percent while Riskowski et al. (1977) cited a value of 22 percent.

5.5 Bird Sensible and Latent Heat

A bird's latent heat production rate is influenced by factors both within and beyond its control. It utilizes both behavioural and physiological processes to adapt to its thermal environment; these have been discussed in the literature review. The pertinent factors beyond the bird's

Table 5.8 SUMMARY OF MOISTURE PRODUCTION DATA DAY AND NIGHT FOR THE TWO BARNS - OVERALL MEAN MEASURED VALUES.

BARN	A		B	
PERIOD	Day	Night	Day	Night
Moisture production, g/(h.bird)	1.65	1.34	3.22	1.77
(range)	(0.6/2.3)	(0.7/2.0)	(1.4/5.3)	(0.9/3.0)
Percentage reduction, day to night, %	19		45	

control are related mainly to management, more particularly, the building environment, lighting schedule, and stocking density. The total, latent, and sensible heat production measured in Barns A and B for each run are given in Table 5.9.

Total heat production of the pullets included both sensible and latent heat. The quantity of sensible heat produced that was being converted to latent heat within the building could not be measured directly by the experimental methods used in this study. The total latent heat comprised both the bird latent heat and the building latent heat. Some of the bird's sensible heat was used to evaporate moisture from the litter/droppings and, hence, only the remaining fraction could be measured directly. Therefore, more latent heat and less sensible heat may appear to be produced under commercial conditions than in calorimeter studies.

The total latent heat production calculated in this study, as previously explained, ranged from 1.4 to 5.6 kJ/(h.bird) (2-90 days) and from 1.1 to 10.0 kJ/(h.bird) (2-134 days), with mean values of 3.4 and 6.6 kJ/(h.bird), for Barns A and B, respectively (Table 5.9). Latent heat production rates as expected were higher in Barn B than in Barn A due to the higher total heat production, higher ambient temperatures and lower relative humidities that prevailed in this facility. Production rates increased with age and, hence, with bird size over the rearing cycle in both barns. Total latent heat production rates, for layers,

Table 5.9 TOTAL, LATENT, AND SENSIBLE HEAT PRODUCTION OF THE REPLACEMENT PULLETS IN BARNS A AND B.

Bird age,	Total heat	Sensible heat	Total latent	Bird[1] latent	Building latent	Total latent/ Total	Sensible heat converted
Days	------------kJ/(h.bird)----------					heat	%
BARN A:							
10	2.4	1.0	1.4	0.4	1.0	0.58	50
36	6.7	4.5	2.2	1.6	0.6	0.33	12
61	14.3	9.9	4.4	3.0	1.4	0.31	12
90	19.6	14.0	5.6	5.1	0.5	0.29	3
BARN B:							
6	2.3	1.2	1.1	0.5	0.6	0.48	33
35	13.3	7.9	5.4	2.0	3.4	0.41	30
63	19.2	12.3	6.9	3.3	3.6	0.36	23
93	27.2	19.0	8.2	4.5	3.7	0.30	16
113	27.7	19.5	8.2	5.5	2.7	0.30	12
134	30.5	20.5	10.0	6.4	3.6	0.33	15

[1] Estimated from calorimetric data (Scott et al., 1983; Longhouse et al., 1968)

cited by DeShazer et al. (1970), Olson et al. (1974), Riskowski et al. (1977), and Feddes et al. (1984b) were 6.0, 5.6, 4.4, and 5.0 kJ/(h.kg), respectively. The corresponding values for the pullets in Barn B ranged from 14.7 to 7.5 (mean: 10.3) kJ/(h.kg).

Broiler latent heat production rates were cited by Deaton et al. (1969) to range from 19.9 to 12.4 kJ/(h.kg) for 4 to 8-week old birds. Feddes et al. (1984a) found values ranging from 31 to 18.3 (5-44 days) kJ/(h.kg) in two broiler barns while the corresponding values for the pullets in Barn A ranged from 18.9 to 5.4 (2-90 days) kJ/(h.kg).

Exposure of birds to warm or cool environments causes a change in conductive, convective, and radiative heat losses of the bird and, consequently, the sensible heat loss. The rate of bird sensible heat production was calculated by deducting the latent heat production from the total heat production. Accordingly, the sensible heat production ranged from 1.0 to 14.0 kJ/(h.bird) (2-90 days) and from 1.2 to 20.5 kJ/(h.bird) (2-134 days) with mean values of 7.4 and 13.4 kJ/(h.bird) for Barns A and B, respectively (Table 5.9). The amount of sensible heat produced increased with bird age and was influenced by ambient temperatures and relative humidity in both barns. Feddes et al. (1984b) noted a mean sensible heat production of 14.8 kJ/(h.kg) in three layer units while Feddes et al. (1984a) reported a mean value of 27.1 kJ/(h.kg) (5-44 days) for two broiler barns. The corresponding values for this study were 18.0 and 14.6 kJ/(h.kg) for Barns B (2-134 days) and A (2-90 days), respectively.

The ratio of total latent heat to total heat ranged from 0.29 to 0.58 and from 0.30 to 0.48 for Barns A and B, respectively (Table 5.9). The narrow range for Barn B indicated that the total heat load for this cage facility consisted of a relatively constant ratio of sensible to latent heat loads throughout the rearing cycle. A greater variation was evident in Barn A due to greater variations in ambient temperature (Table 5.1).

Feddes et al. (1984a) observed a mean ratio of 0.49 (range: 0.36 to 0.70) for broilers under winter conditions. The higher ratio found by these authors than that found in Barn A (0.38) may be due, in part, to the higher ambient temperatures and, consequently, greater evaporative heat loss present in the broiler units than in pullet facilities. Feddes et al. (1984b) also reported a ratio of 0.26 for layers in cage facilities and noted that the relationship between the ambient temperature and latent to total heat production ratio, as developed by Charles and Spencer (1976), agreed with these data and data of other researchers. The mean ratio measured in Barn B was 0.36 but this value probably can not be applied fully to the above relationship due to its applicability to mature fowl only.

To estimate the moisture evaporated from within the building, calorimetric moisture production data of DeShazer et al. (1970) and van Kampen (1976), as cited by Scott et al. (1983) for laying birds, and of Longhouse et al. (1968) for broilers, were used. These data are the most valid information available. The values found by these authors, based on bodyweight, were averaged to a value of 2.0 g moisture/(h.kg) or 4.9 kJ/(h.kg). This latter value, adjusted for bird weight, was termed the bird latent heat (Table 5.9). This bird latent was subtracted from the measured total latent heat to give an approximation of the amount of sensible heat conversion that had occurred (Table 5.9).

The bird latent ranged from 0.4 to 5.1 kJ/(h.bird) (2-90 days) and from 0.5 to 6.4 kJ/(h.bird) (2-134 days) with mean values of 2.5 and 3.7 kJ/(h.bird) for Barns A and B, respectively. The latent heat produced by the birds increased with age over the rearing cycle in both barns.

The amount of bird sensible heat that was used to evaporate moisture from the litter/droppings pit was termed the building latent heat, that is, latent heat other than bird latent. The building latent heat ranged from 0.5 to 1.4 kJ/(h.bird) (2-90 days) and 0.6 to 3.7 kJ/(h.bird) (2-134 days) for Barns A and B, respectively (Table 5.9).

Feddes et al. (1984a) noted that, in broiler barns, the building latent heat ranged from 24.5 to 12.0 (mean: 17.2) kJ/(h.kg) while that in Barn A ranged from 13.5 to

0.4 (mean: 4.6) kJ/(h.kg). The discrepancies in the results may be attributed to the much higher sensible heat production for broilers than for pullets. In three layer units, Feddes et al. (1984b) reported mean building latent heat values of 1.1 kJ/(h.kg) while the corresponding value for Barn B was 5.1 (range: 8.0 to 2.9) kJ/(h.kg).

The percentage of sensible heat converted to latent heat decreased with increasing bird age and decreasing ambient temperature for both barns, with the mean values being slightly lower and more variable in Barn A than in Barn B. These measured values ranged from 3 to 50 (mean: 19.3) percent and 12 to 33 (mean: 21.5) percent over the rearing cycle for Barns A and B, respectively (Table 5.9). Feddes et al. (1984a) determined that the percentage of bird sensible heat converted to latent heat in broiler barns ranged from 28 to 69 (mean: 42) percent. The combined effect of high ambient temperature, low relative humidity, and high bird sensible heat production appeared to contribute to the high conversion values in these broiler facilities. Feddes et al. (1984b) also reported a mean sensible heat conversion of 7.0 percent for three layer units. The litter, in Barn A, became very dry towards the end of the production cycle as shown by the negligible amount of sensible heat converted (3 percent) and was influential in the high dust concentrations found within this unit.

5.6 Carbon Dioxide Production

When birds respire they exhaust CO_2 into the atmosphere. In a confinement building, this contaminated air is removed by ventilation. Therefore, the concentrations of CO_2 and other air contaminants within poultry barns are influenced greatly by the air exchange rate. The production of CO_2 is a function of metabolic rate and, therefore, related to heat production rates. Carbon dioxide concentrations were measured at five sampling locations in Barn A, and six in Barn B, three times hourly, for each monitoring period. The CO_2 production rates for each barn were calculated from the product of air-flow rates and the difference in CO_2 concentrations of the inlet and outlet air.

Hourly CO_2 production rates for Barns A and B are shown in Figures 5.11 and 5.12, respectively. These figures are similar to the heat production curves in Figures 5.5 and 5.6, respectively, due to CO_2 production rates being a function of metabolic rate. The diurnal variations in CO_2 production also were similar to moisture removal rates (Figures 5.8 and 5.9, respectively).

Production rates in Barn A for the second run and for the other monitoring periods were relatively constant during the night (300 mL/(h.bird)) while greater and more variable rates were exhibited during the day. These trends may be attributed to bird inactivity at night and a lower metabolic rate. Carbon dioxide production in Barn B showed

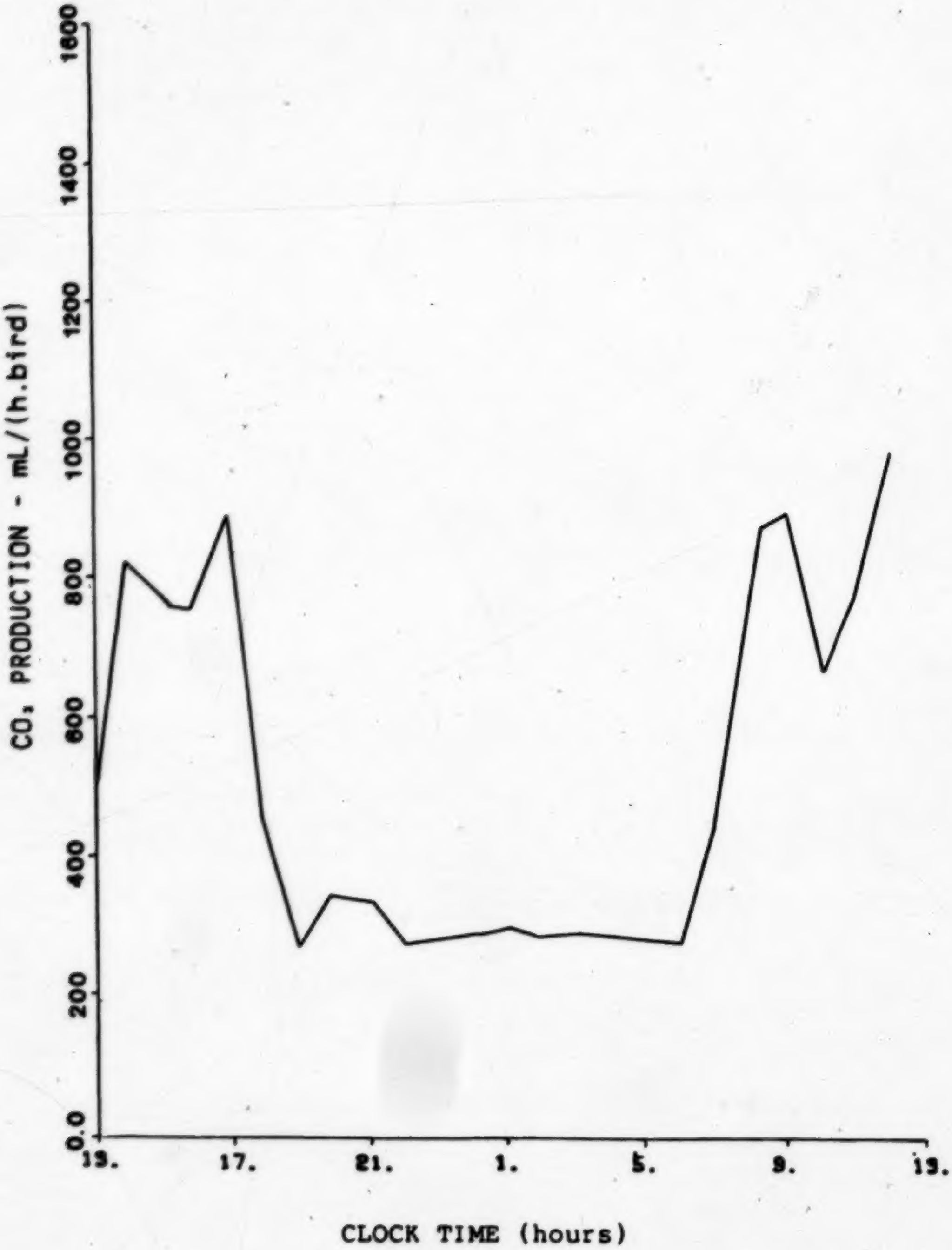


Figure 5.11 Mean hourly carbon dioxide production rates in Barn A with 36-day old replacement pullets.

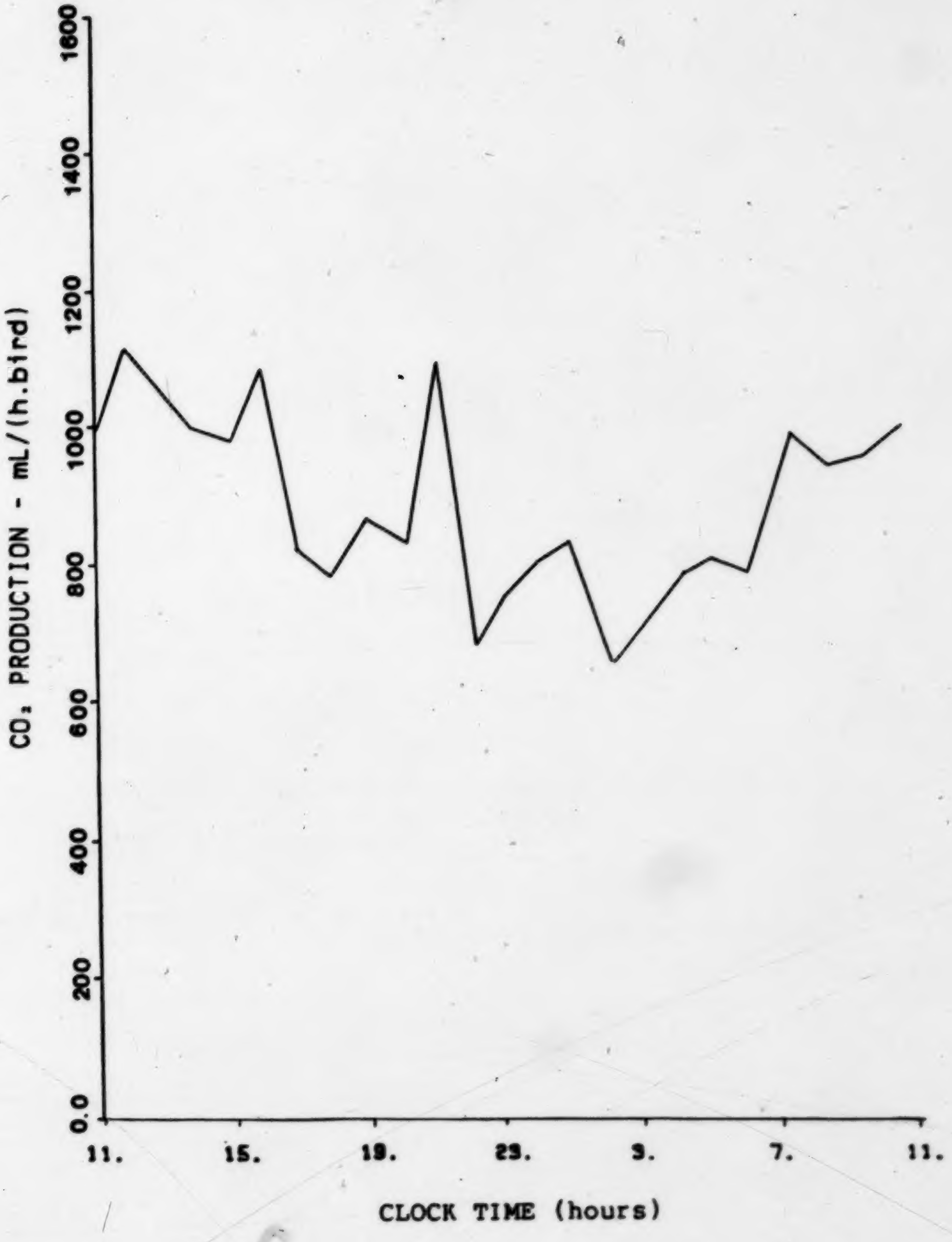


Figure 5.12 Mean hourly carbon dioxide production rates in Barn B with 35-day old replacement pullets.

greater variation during the day than that in Barn A for all the runs. Noise from the feeders and a resultant increase in bird activity were reflected in these figures, as also was observed in Figures 5.5 and 5.6.

The mean CO_2 concentrations measured in this study were not great enough to be considered a health hazard to either birds or humans when exposed to this gas, as previously reviewed by McQuitty and Feddes (1982). The time-weighted TLV for CO_2 concentrations in the industrial workplace is 5000 ppm (ACGIH, 1984). The mean exhaust CO_2 concentrations ranged from 1970 to 2880 ppm and from 2069 to 3466 ppm for Barns A and B, respectively (Table 5.10). Exhaust concentrations in Barn A also were relatively constant except for the last two runs while those of Barn B varied during the first half of the rearing cycle. The CO_2 concentrations were slightly higher at the exhaust locations than at ambient except for the first run in Barn B and the third and fourth runs in Barn A, suggesting some incomplete mixing in both barns.

Carbon dioxide production rates ranged from 251 to 741 mL/(h.bird) in Barn A (2-90 days) and from 341 to 2093 mL/(h.bird) in Barn B (2-134 days) over the rearing cycle. As before, comparisons are made on a bodyweight basis. Leonard et al. (1984b) found that production rates in two broiler barns ranged from 3.3 to 2.4 (mean: 2.8) L/(h.kg) while the corresponding values in Barn A ranged from 3.4 to 0.7 (mean: 1.6) L/(h.kg). McQuitty et al. (1984) also

Table 5.10 MEAN CARBON DIOXIDE PRODUCTION AND CONCENTRATION DATA AND VENTILATION RATES FOR THE TWO BARNS.

Bird age, days	CO_2 concentration[1] Ambient[2]	 Exhaust[3]	Ventilation rate L/(s.bird)	CO_2 production mL/(h.bird)
	--- ppm	-----		
BARN A:				
10	1950	1970	0.04	251
36	1910	2010	0.10	510
61	2080	2070	0.12	600
90	2930	2880	0.10	741
118	2660	2760	0.90	663
BARN B:				
6	2830	2800	0.05	341
35	2890	3470	0.10	896
63	2150	2580	0.19	1256
93	1870	2240	0.33	1766
113	1800	2210	0.36	1921
134	1670	2070	0.42	2093

[1] excludes 500 ppm CO_2 in outside air

[2] CO_2 concentrations within barn

[3] CO_2 concentrations at fans

reported mean daily rates of 1.0 L/(h.kg) in three layer units, while the mean values measured in Barn B were 2.3 (range: 4.6 to 1.7) L/(h.kg).

The trends in all these CO_2 data followed similar trends to heat production rates. The lower CO_2 production rates in Barn A than in Barn B suggested that the pullets in the former barn were receiving a lower energy intake in their feed than in Barn B.

Table 5.11 gives the mean CO_2 production and concentration data during day and night periods for both barns monitored. As in heat production, light influences metabolic rate and, in turn, CO_2 production rate. There was little difference in CO_2 concentrations between ambient and exhaust during the light periods of both barns with a more noticeable difference (300 ppm) in Barn B than in Barn A. A similar trend was observed for the dark period in both barns (Table 5.11). As expected, the production rates were higher during the day than during the night due to the activity of the birds.

The mean reduction in CO_2 production rates from day to night was 39 and 30 percent for Barns A and B, respectively. McQuitty et al. (1984) reported a mean reduction in CO_2 production rates from day to night of 30 percent for layers. The findings of these authors related favorably to those measured in the cage facility in this study. The mean CO_2 production and concentration data for both barns during day and night periods are given in

Table 5.11 OVERALL MEAN CARBON DIOXIDE PRODUCTION AND CONCENTRATION DATA DURING DAY AND NIGHT PERIODS.

BARN	A		B	
PERIOD	Day	Night	Day	Night
CO_2 production, mL/(h.bird)	669	404	1622	1173
(range)	(312/908)	(200/600)	(466/2538)	(235/1870)
Percentage reduction, day to night	39.0		30.1	
CO_2 ambient, ppm	2460	2020	2260	2160
CO_2 exhaust, ppm	2490	2010	2560	2560

Appendix H.

The best-fit equations, used to relate CO_2 production rates and bird age, were a polynomial function of degree two for both barns, similar to the other production curves found in this study. These equations were plotted in Figure 5.13. As shown in this figure, the CO_2 production rates differed for the two barns. The differences in the production curves for the two barns remained relatively constant for total heat (Figure 5.7) but diverged for CO_2 production, over the rearing cycle. Carbon dioxide production rates in Barn B were higher and increased more rapidly with bird age than those in Barn A, reflecting the apparent higher level of feed intake in Barn B. These best-fit equations, which have a high degree of correlation ($R^2 = 0.96, 0.99$) for Barns A and B, respectively, are as follows:

$$Y = 163.39 + 73.304X - 2.2639X^2 \qquad (16)$$

and

$$Y = 212.83 + 143.957X - 2.3475X^2 \qquad (17)$$

where Y = CO_2 production rate, mL/(h.bird), and
X = age of the birds, weeks.

Similar type equations were developed for the corresponding light and dark periods of both barns, for completeness:

Barn A -

Day: $Y = 212.87 + 104.33X - 4.103X^2$ (18)

Night: $Y = 120.87 + 47.16X - 0.707X^2$ (19)

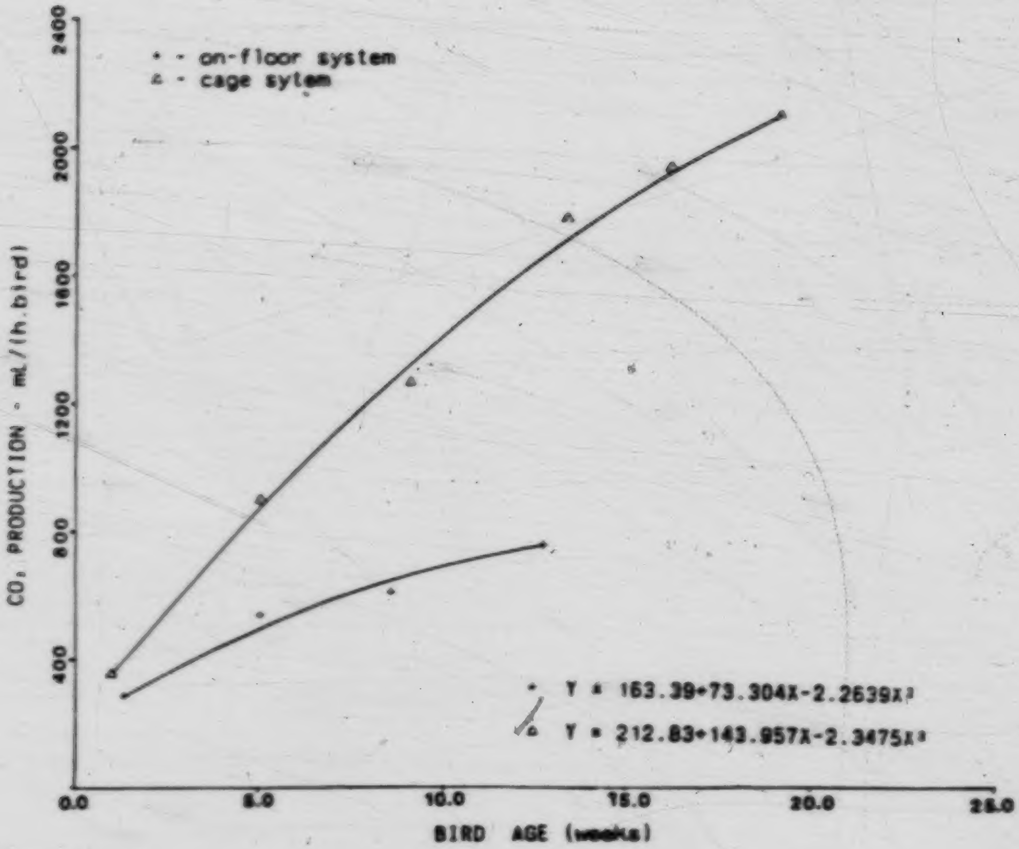


Figure 5.13 Carbon dioxide production of replacement pullets in Barns A and B during complete production cycles.

Barn B -

Day: $Y = -74.19 + 237.51X - 5.752X^2$ (20)

Night: $Y = 171.98 + 114.88X - 1.407X^2$ (21)

These best fit equations also have a high degree of correlation ($R^2 = 0.85, 0.97, 0.99, 0.99$, respectively).

Carbon dioxide is a product of the birds' metabolism which, in turn, is dependent upon food energy intake, environmental temperature, and activity. This concept formed the basis for an equation developed by Bruce (1981) relating metabolism and CO_2 production for swine. He also suggested that ventilation rates could be based on the CO_2 concentration within the animal building when the number of animals and their age or weight are known. Leonard et al. (1984b) found that ventilation rates in broiler barns could be expressed as the ratio of a constant times the number and weight of birds to the CO_2 concentration. In addition, bird weight was included in the relationships established in this study as the birds bodyweight was changing continuously over the rearing cycle. The relationships between the ventilation rates, bird weight, number of birds, and the CO_2 concentrations found in this study for Barns A and B, respectively, are as follows:

$$V = 288\ W^{0.4}\ B/(D-E) \qquad (22)$$

and

$$V = 745\ W^{0.6}\ B/(D-E) \qquad (23)$$

where V = ventilation rate, L/(s.bird),

W = average bird weight, kg,

B = number of birds,

D = exhaust CO_2 concentration, ppm, and

E = outside CO_2 concentration, ppm.

The CO_2 production rate for the last run in Barn A was not used in equation 22 due to a reduction in feed intake and, consequently, a reduction in CO_2 production. The above relationships could be useful to extension personnel when trouble-shooting ventilation problems. For this reason, only day-time values were given as this is the normal working period for extension staff. The exhaust CO_2 concentrations were used in the above calculations as the fans present the most consistent locations for measurements in barns with incomplete mixing. Therefore, by knowing the CO_2 concentration of the exhaust air, the number of birds and bird weight in the replacement pullet barn, the ventilation rates may be determined from equations 22 and 23.

5.7 Ammonia Production

Concentrations of NH_3 in both barns were measured three times hourly over each monitoring period. These measurements were converted to mean hourly concentrations and then into hourly production rates utilizing the corresponding mean hourly ventilation rate.

Examples of NH_3 production rates are shown in Figures 5.14 and 5.15 for Barns A and B, respectively. During this second and other runs, the release of NH_3 into the bird environment in Barn A was greater and more

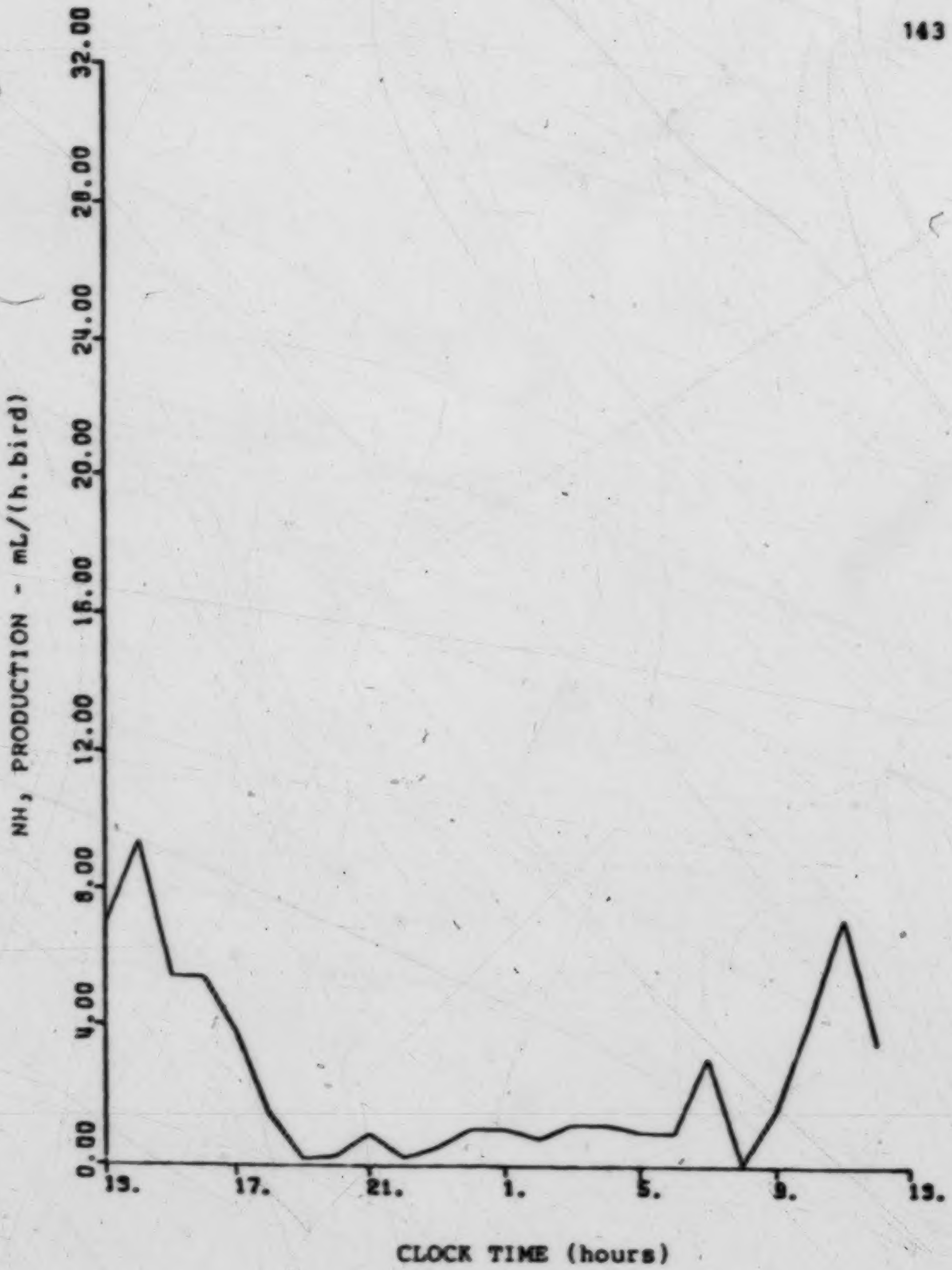


Figure 5.14 Mean hourly ammonia production rates in Barn A with 36-day old replacement pullets.

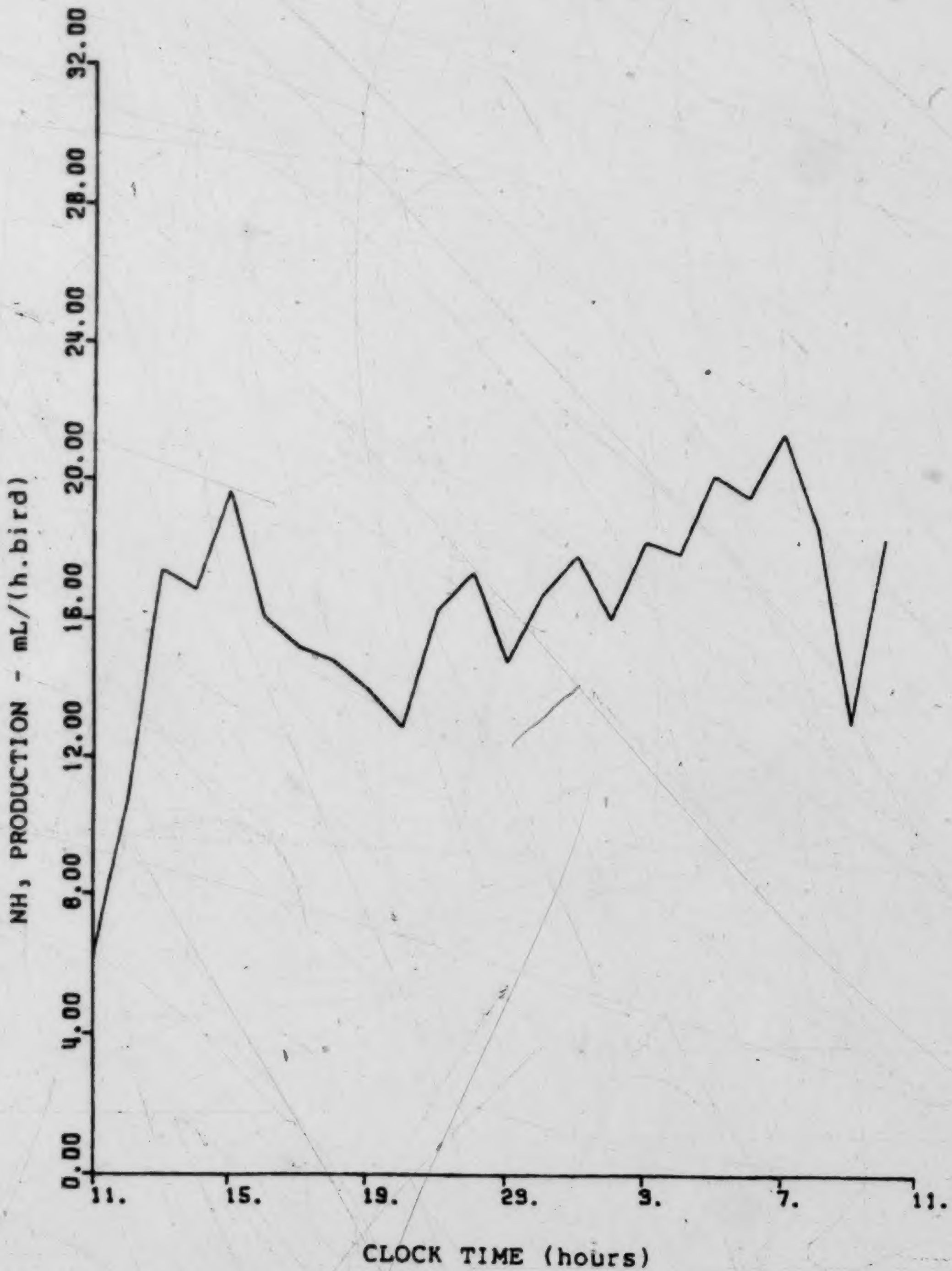


Figure 5.15 Mean hourly ammonia production rates in Barn B with 35-day old replacement pullets.

variable during the day than during the night (Figure 5.14). The production of NH_3 in Barn B (Figure 5.15) fluctuated over the 24-hour period, particularly during the night. In addition, the production rates in this cage facility were slightly greater during the night than during the day for this monitoring period even though the ventilation rates were higher during the day (Figure 5.4). However, the production rates were greater during the day than during the night in this facility for the other runs. Consequently, the ambient air mass appeared to act as an NH_3 sink during the day and as a source during the night. The NH_3 concentrations and production rates and ventilation rates for both barns are tabulated in Table 5.12.

The ambient concentrations of NH_3 ranged from 0 to 25 ppm and from 3 to 38 ppm, with mean values of 14 and 10 ppm for Barns A and B, respectively (Table 5.12). The concentrations of NH_3 recorded in Barn A during the later stages of the production cycle were above the acceptable level of 20 ppm suggested for poultry (Sainsbury, 1980). The concentrations in Barn B were lower than those in Barn A due to the higher ventilation rates that existed in the former, coupled with a lower rate of production over most of the period from the pit-stored droppings than from the litter. The high NH_3 concentration and production rate found in Barn B during the second monitoring period were due to the droppings pits being cleared out just prior to the commencement of monitoring.

Table 5.12 MEAN AMMONIA PRODUCTION AND CONCENTRATION DATA AND VENTILATION RATES FOR THE PULLET BARNS.

Bird age, days	NH$_3$ concentration		Ventilation rate L/(s.bird)	NH$_3$ production mL/(h.bird)
	Ambient	Exhaust		
	----- ppm -----			
BARN A:				
10	0	0	0.04	0.0
36	5	6	0.10	2.1
61	16	17	0.12	7.3
90	25	24	0.10	8.3
118	22	21	0.09	6.4
BARN B:				
6	8	9	0.05	1.5
35	38	53	0.09	16.2
63	5	8	0.19	5.1
93	3	5	0.33	5.0
113	4	4	0.36	5.2
134	3	4	0.42	6.0

Concentrations of NH_3 in the exhaust air were measured throughout the rearing cycle. These data ranged from 0 to 24 ppm and from 4 to 53 ppm, with mean values of 14 and 17 ppm for Barns A and B, respectively (Table 5.12). There was very little difference in concentrations between the ambient and exhaust air throughout the production cycle for both barns except during the second run in Barn B, when concentration levels were exceedingly high. However, the mean concentration of NH_3 in the ambient air in Barn B was lower than that in the exhaust air. This observation also was consistent with the higher exhaust CO_2 concentration and higher exhaust temperatures measured than those in the ambient air. This is similar to the findings of McQuitty et al. (1984) in a layer barn for both triple-deck and shallow-gutter facilities but not for the deep-pit unit. The trend in Barn A was not as apparent.

Production rates for NH_3 measured in this study ranged from 0.0 to 8.3 mL/(h.bird) for Barn A and from 1.5 to 16.2 mL/(h.bird) for Barn B (Table 5.12). The NH_3 data for Barn A showed that the rate of production increased markedly with time although the rate increase slowed when half the birds were removed at 6 weeks.

A best-fit curve relating NH_3 production with bird age only was established for the data in Barn A and is presented in Figure 5.16. The frequent removal of the droppings from the droppings pits in Barn B prevented any continuous relationship over the rearing cycle. The

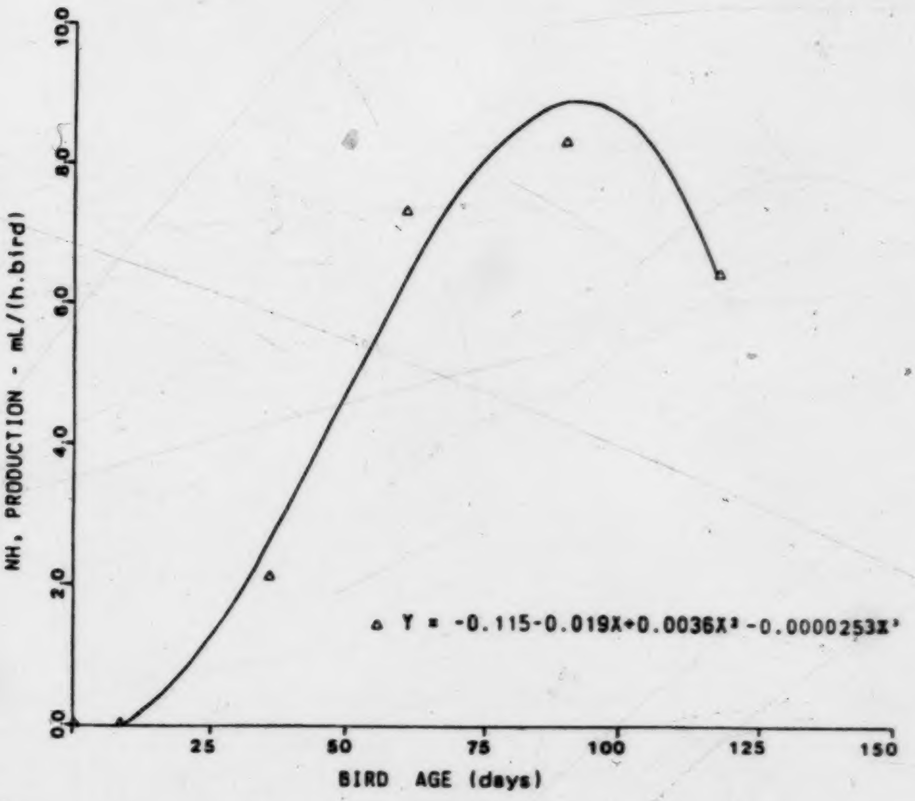


Figure 5.16 Ammonia production rates in Barn A during complete production cycle.

equation relating NH_3 production (Y), expressed as mL/(h.bird), with bird age in days (X) was as follows (R^2= 0.98):

$$Y = -0.115 - 0.019X + 0.0036X^2 - 0.0000253X^3 \quad (24)$$

Rate of production in this facility up to 6 weeks appeared to follow a trend similar to that found by Leonard et al. (1984b) in two broiler barns. These authors established an exponential relationship for the above two parameters over the broiler production cycle. A similar pattern was observed by McQuitty et al. (1984) for the first five weeks after droppings removal in a shallow-gutter cage layer facility.

Rate of NH_3 production is influenced by the amount of litter/droppings present in the barns..In this regard, the data measured for pullets in Barn A were compared on a floor area basis with that found by Leonard et al. (1984b) for broilers under winter conditions. Leonard et al. (1984b) noted that NH_3 production rates ranged from 6.5 to 22.6μL/(h.m^2.bird) in broiler units while the values in Barn A ranged from 0.0 to 34.2 μL/(h.m^2.bird) over the rearing cycle. These data also illustrated the importance of removing the litter on which replacement pullets have been reared previously. Several authors, including Reece (1979), Reece et al. (1981) and Moulsley (1977), observed that young chickens were less resistant to disease due to the use of old litter. The NH_3 data for Barn B increased rapidly during the first two runs and thereafter decreased to low levels of production, even though the ventilation rates were increasing (Table 5.12). McQuitty et al. (1984) found mean daily production rates ranging from 10.2 to 68.0μL/(h.m^2.bird) in three layer facilities under winter conditions while the corresponding values in Barn B ranged from 3.0 to 32.4μL/(h.m^2.bird) over the production cycle. The total floor area was used in each of the above data.

The NH_3 concentration and production rates during the light and dark periods are shown in Table 5.13. The overall mean ambient concentrations of NH_3 measured were 15 and 9 ppm during the day and 13 and 11 ppm during the night for Barns A and B, respectively (Table 5.13). These overall means included the mean concentrations measured for the last run in Barn A as NH_3 formation was not related directly to bird feed intake. However, these values for this run may be low due to the prevailing low ambient temperatures within this unit (Table 5.1).

The concentrations of NH_3 in the exhaust air followed similar trends to that in the ambient air with mean values of 15 and 12 ppm during the day and 12 and 15 ppm during the night for Barns A and B, respectively (Table 5.13). McQuitty et al. (1984) found more than double these concentrations during both periods for layers in deep-pit and shallow-gutter units but somewhat less in a triple-deck facility.

Mean production rates of NH_3 measured in this

Table 5.13 OVERALL MEAN AMMONIA PRODUCTION AND CONCENTRATION DATA DURING DAY AND NIGHT PERIODS.

BARN	A		B	
PERIOD	Day	Night	Day	Night
NH_3 exhausted, mL/(h.bird) (range)	5.6 (0.0/9.0)	4.1 (0.0/7.6)	7.1 (2.1/15.7)	5.9 (1.0/16.6)
Percentage reduction day to night, %		27		17
NH_3 ambient, ppm	15	13	9	11
NH_3 exhaust, ppm	15	12	12	15

study ranged from 0.0 to 9.0 mL/(h.bird) and from 2.1 to 15.7 mL/(h.bird) during the day for Barns A and B, respectively (Table 5.13). Corresponding values during the night ranged from 0.0 to 7.6 mL/(h.bird) and from 1.0 to 16.6 mL/(h.bird) for Barns A and B, respectively (Table 5.13). Production rates were greater during the day than during the night in both barns. The reduction in NH_3 production rates between the light and dark periods for Barns A and B were 27 and 17 percent, respectively. These results differed from those reported by McQuitty et al. (1984) for cage layers. These authors found no variations in NH_3 concentration and production rates from day to night in all three facilities and suggested that lighting schedule had no apparent effect on production rates.

5.8 Hydrogen Sulphide

The presence of H_2S in confinement animal units is of major concern due to its lethal nature when high concentrations exist, particularly during agitation of manure pits. However, Barber and McQuitty (1974) reported that H_2S concentrations were normally very low or undetectable. The time-weighted TLV for H_2S in the industrial workspace is 10 ppm (ACGIH, 1984). The air in the two barns studied was monitored for concentrations of H_2S. The sulphur analyzer sampled the air for approximately 20 minutes during each run. This analyzer was capable of measuring H_2S concentrations as low as 10 ppb. Hydrogen sulphide concentrations were undetectable in Barn A during any of the trial runs (Table 5.14). This may be attributed to the aerobic decomposition of the litter and reflected the low moisture levels within the litter.

The mean concentrations of H_2S recorded in Barn B ranged from 10 to 142 ppb (Table 5.14). The measured values in this barn doubled over the first two runs and then steadily declined for the remainder of the production cycle. The highest concentrations found in Barn B occurred during the second monitoring period. This also coincided with the highest NH_3 concentrations found during this same period in which the contents of the droppings pits were agitated.

Higher H_2S concentrations were expected in Barn B than in Barn A due to the anaerobic decomposition of the semi-liquid droppings in the pits and frequent disturbance of these stored droppings, as observed by Ludington et al. (1969). Due to the frequency of cleaning, and to the method of handling the droppings, any danger due to H_2S was probably minimal in this cage facility. However, the presence of H_2S suggests that caution should be exercised, particularly during cleaning of the pits, until additional data on H_2S are obtained in barns utilizing this droppings handling system under a variety of conditions. Leonard et al. (1984b) and McQuitty et al. (1984) also could not detect any H_2S in broiler and cage layer barns, respectively, except in a deep-pit facility where concentrations reached a maximum of 30 ppb.

Table 5.14 MEAN HYDROGEN SULPHIDE LEVELS IN THE TWO PULLET BARNS.

	Bird age, days	H_2S concentration, ppb
BARN A:		
	H_2S never exceeded 10 ppb	
BARN B:		
	6	70
	35	142
	63	69
	93	58
	113	36
	134	10

5.9 Dust Concentrations

Concentrations of dust were monitored in both barns to ascertain dust levels in commercial replacement pullet facilities and to determine whether these concentrations might be considered detrimental to bird and/or operator health. Dust particle counts were allocated two overall size ranges which were averaged into mean hourly concentrations and also averaged on the basis of lighting schedules. The daily mean concentration data are tabulated in Table 5.15.

As a result of high concentrations and the adhesive quality of the dust, the particle counter suffered repeated calibration problems. The data were not collected, therefore, with the pullets at the same stage of growth in the two barns, making direct comparison of respective data difficult. The time-weighted TLV's for nuisance dust in industrial situations, as aforementioned, are 1060 particles/mL but only 420 particles/mL if air contains particle sizes less than 5μm (ACGIH, 1984). Thus, TLV's for animal environments should be somewhat lower than those in industry. Dust data were obtained for the first and last run in Barn A and for a total of three runs in Barn B (Table 5.15). Of the data collected, however, Barn A was found to have high dust particle concentrations over the monitoring period, particularly in the size range less than 5μm. For this size range, the daily concentrations ranged from 36 to 100 particles/mL and from 3.2 to 18.9 particles/mL for

Table 5.15 MEAN DUST CONCENTRATIONS IN TWO BARNS (particles/mL).

Bird age, days	Light <5um	Light >5um	Dark <5um	Dark >5um	Daily <5um	Daily >5um
BARN A:						
10	52.0	1.4	22.0	0.3	36.0	0.8
118	150.0	34.0	62.0	7.3	100.0	19.0
BARN B:						
63	3.5	0.5	3.0	0.5	3.2	0.5
93	13.0	1.3	13.0	1.3	13.0	1.3
134	8.3	0.9	28.3	1.2	18.9	1.1

Barns A and B, respectively (Table 5.15).

For particles greater than 5μm, the concentrations ranged from 0.8 to 19.0 particles/mL and from 0.5 to 1.3 particles/mL for Barns A and B, respectively. Leonard et al. (1984b) reported a maximum daily mean concentration of dust less than 5μm of 6.8 particles/mL and that of particles greater than 5μm of 1.3 particles/mL in a study involving commercial broiler facilities under winter conditions. These authors used the same type of instrumentation and similar procedures in obtaining their data as those utilized in this study. In a similar study, McQuitty et al. (1984) found mean daily concentrations of 7.9 and 0.3 particles/mL for sizes less than and greater than 5μm, respectively, in three cage layer facilities.

In Barn A, the dust concentrations during the night, in both size categories, were found to be less than half the daytime values while those in Barn B remained relatively constant (Table 5.15). The mean dust particle concentrations in the size range less than 5μm ranged from 52.0 to 150.0 particles/mL and 3.5 to 13.0 particles/mL during the light period, and from 22.0 to 62.0 particles/mL and 3.0 to 28.3 particles/mL during the night period for Barns A and B, respectively. In both barns, periodic extremes were measured. These are thought to be due primarily to disturbances of the chickens. McQuitty et al. (1984) found maximum mean concentrations for the light and dark periods of 39.7 and 14.4 particles/mL for sizes less than 5μm, and 1.3 and 0.4 particles/mL for sizes greater than 5μm, respectively, in a study of cage layer operations using the same equipment and sampling methods. Thus, dust concentrations measured in Barn A far exceeded values found in any other poultry facilities using the same monitoring techniques.

Sainsbury (1980) suggested that relative humidities within poultry barns should be maintained above 50 percent. If not so maintained, the litter becomes too dry and dust concentrations increase, with the result that there is an increased challenge to the respiratory system with increased risks of infection. Therefore, the interactions of low relative humidities, dry litter, and low ventilation rates that were evident in Barn A, caused an unneccessary stress upon the pullets within this facility. In addition, 20 to 30-mm layers of dust were observed on permanent fixtures, such as the heating pipes, within this unit.

The time spent each day in the barn by the producers varied. In Barn A, the barn was entered about once a day for about 15 minutes. Entry was discouraged to minimize 'piling' of birds in corners. In Barn B, several hours each day were spent by the operator in the barn. Dust-covered surfaces, such as the cages and fan shrouds, were swept clean every two days. The walkways were washed down with water every three days to minimize dust concentrations. The low concentrations of dust in Barn B were considered to be a result of both exemplary management techniques, and the cage system.

Curtis (1981) noted that dust particles have the capability for absorbing gases. Thus, the smaller particles in conjunction with NH_3 can be detrimental to operator and bird health if they succeed in reaching the lungs. Therefore, the combination of dust and NH_3 found in Barn A would appear to represent a potentially hazardous environment and a challenge to the birds' respiratory system.

6.0 Conclusions

Based on the results obtained in this study, the following conclusions were drawn:

1. Total heat production of the replacement pullets was higher in the cage bird system than in the on-floor system, with values ranging from 2.3 to 30.5 kJ/(h.bird) over the period of the production cycle.
2. Moisture production rates ranged from 0.7 to 4.1 g/(h.bird) over the period of the production cycle being highest in the barn utilizing cages.
3. The total heat output, moisture and carbon dioxide production can be predicted accurately, using regression equations with bird age as the only variable.
4. The replacement pullet barns were found to have excessive ventilation rates in terms of moisture control for the prevailing conditions, resulting in low relative humidities (37 to 64 percent).
5. The actual conversion of sensible to latent heat varied widely over the rearing cycle in both barns, being more variable in the on-floor unit.
6. Carbon dioxide concentrations were considered to be low in terms of health hazards (range: 1670 to 2930 ppm).

7. Ammonia concentrations were considered to be potentially hazardous in the unit with on-floor rearing, the concentrations exceeding 20 ppm for most of the production cycle.
8. Ammonia production increased exponentially for the first six weeks in the on-floor unit but levelled off after the stocking density was reduced after 6 weeks by more than 50 percent. This suggests that litter should not be re-used.
9. Hydrogen sulphide concentrations were detected only in the cage unit and at very low values, but indicating the possibility of a hazardous environment during clean-out operations.
10. Dust concentrations reached 150 particles/mL and showed significant diurnal changes in the on-floor unit. Dust concentrations in the cage unit remained relatively constant at low levels.
11. The synergistic effect of NH_3 and dust concentrations in the on-floor unit represented a potentially hazardous environment.
12. Management practice and building design appeared to have a very significant effect on air quality parameters.
13. Concentrations of air contaminants were influenced by ventilation rates, feed intake, and droppings/litter handling methods.

7. LITERATURE

American Conference of Governmental Industrial Hygienists. 1984. Threshold limit values for substance in workroom air with intended changes for 1984. American Conference of Governmental Industrial Hygienists, P.O. Box 1937, Cincinnati, Ohio 45201.

American Society of Agricultural Engineers. 1984. Agricultural Engineers Handbook of Standards. Amer. Soc. Agric. Eng., St. Joseph, MI. pp. 412-421.

American Society of Heating Refrigeration and Air Conditioning Engineers. 1978. Handbook of Fundamentals. ASHRAE, Inc., Atlanta, Georgia.

American Society of Heating Refrigeration and Air Conditioning Engineers. 1981. Method of testing air cleaning devices used in general ventilation for removing particulate matter. ASHRAE Code 52-78. ASHRAE, Inc., Atlanta, Georgia.

Adams, A.W. and M.E. Jackson. 1970. Effect of cage size and bird density on performance of six commercial strains of layers. Poult. Sci., 49: 1712-1719.

Agricultural Research Council. 1974. The Nutrient Requirements of Farm Livestock. Report No. 1. Poultry, 2nd ed., Agricultural Research Council, London.

Anderson, D.P., C.W. Beard and R.P. Hanson. 1964. The adverse effects of ammonia on chickens including resistance to infection with Newcastle disease virus.

Avian Diseases, 8: 369-379.

Aschoff, J. and R. Wever. 1958. Kern und Schale in Warmehaushalt des Menschen. Naturwissenschaften, 45: 477-485. (Cited by Mount (1979)).

Associate Committee on the National Building Code. 1977. Canadian Code for Farm Buildings. National Research Council of Canada, Ottawa.

Baile, C.A. and J.M. Forbes. 1974. Control of feed intake and regulation of energy expenditure balance in ruminants. Physiol. Rev., 54: 160.

Bailey, B.B., J.H. Quisenberry and J. Taylor. 1959. A comparison of performance of layers in cage and floor housing. Poult. Sci., 38: 565-568.

Baldini, J.T. 1961. The effect of dietary deficiency on the energy metabolism of the chick. Poult. Sci., 40: 1177-1183.

Balnave, D. 1974. Biological factors affecting energy expenditure. In: T.R. Morris and B.M. Freeman (Eds), Energy Requirements of Poultry. Poult. Sci. Symp. No. 9. British Poultry Science Ltd., London. pp. 25-45.

Balnave, D. and N. Jackson. 1973. The effect of quantity of food offered and ad libitum feeding on the metabolizable energy intakes and egg production responses of mature laying hens. 4th Europ. Poult. Conf., London. pp. 211-215.

Barber, E.M. and J.B. McQuitty. 1974. Hydrogen sulphide evolution from anaerobic swine manure. Publ., Dept. of

Agric. Eng., Faculty of Agriculture and Forestry, The University of Alberta, Edmonton, Alberta. pp. 8-19.

Barott, H.G. 1937. Effect of temperature, humidity, and other factors on hatch of hens' eggs and on energy metabolism of chick embryos. Tech. Bull. 553, U. S. Dept. Agric. pp. 1-45.

Barott, H.G. and E.M. Pringle. 1946. Energy and gaseous metabolism of the chicken from hatch to maturity as effected by temperature. J. Nutr., 31: 35-50.

Barott, H.G. and E.M. Pringle. 1947. Effect of environment on growth and feed and water consumption of chickens. I. The effect of temperature of environment during the first nine days after hatch. J. Nutr., 34: 53.

Barott, H.G. and E.M. Pringle. 1949. Effect of environment on growth and feed and water consumption of chickens. II. The effect of temperature and humidity of environment during the first eighteen days after hatch. J. Nutr., 37: 153.

Barott, H.G. and E.M. Pringle. 1950. Effect of environment on growth and feed and water consumption of chickens. III. The effect of temperature of environment during the period from 18 to 32 days of age. J. Nutr., 41: 25.

Barott, H.G. and E.M. Pringle. 1951. Energy and gaseous metabolism of the hen as affected by temperature. J. Nutr., 22: 273-286.

Barott, H.G., J.C. Fritz, E.M. Pringle and H.W. Titus. 1938. Heat production and gaseous metabolism of young male chickens. J. Nutr., 15: 145-167.

Baumgardt, B.R., L.F. Krobill, J.L. Gobble and P.J. Wangsness. 1976. Estimating feed intake for cattle, sheep and swine. In: P.V. Fonnesbeck, L.E. Harris and L.C. Kearl (Eds.), Proc. 1st Inter. Symp. Feed Composition, Anim. Nutr. Req., and Comput. of Diets. Utah State Univ., Logan, Utah. pp. 464-469.

Bell, D., M.H. Swanson, D.R. Kuney and C.J. Adams. 1979. Cage shape: Its effect on layer performance. Poult. Sci., 37: 1187.

Benedict, F.G., W. Landauer and E.L. Fox. 1932. The physiology of normal and frizzle fowl, with special reference to the basal metabolism. Bull. Storrs Agric. Exp. Sta., 177: 13-101. (Cited by Balnave (1974)).

Benzinger, T.H. 1971. Peripheral cold reception and central warm reception, sensory mechanisms of behavioral and autonomic thermostasis. In: J.D. Hardy, A.P. Gagge and J.A.J. Stolwijk (Eds.), Physiological and Behavioral Temperature Regulation. Charles C. Thomas, Springfield, IL. Chapter 56.

Bianca, W. 1968. Thermoregulation. In: E.S.E. Hafez (Ed.), Adaptation of Domestic Animals. Lea and Febiger, Philadelphia. pp. 97-118.

Blaxland, J.D., J. Shemtob, G.H. Francis and G.E. Jones. 1978. Mortality in a battery laying house attributed to the presence of noxious gases from slurry. Vet. Rec. 103: 241-242.

Blaxter, K.L. 1967. The Energy Metabolism of Ruminants. 2nd Ed. Hutchinson and Co. (Publ.) Ltd., London.

Blaxter, K.L. 1970. Sub-committee on constants and factors. In: A. Schurch and C. Wenk (Eds.), Energy Metabolism of Farm Animals, Juris Druck Verlag, Zurich. pp. 14-15.

Bligh, J. 1973. Temperature Regulation in Mammals and Other Vertebrates. American Elsevier Publ., New York.

Boone, M.A. and B.L. Hughes. 1971. Wind velocity as it affects body temperature, water consumption and feed consumption during heat stress of roosters. Poult. Sci., 50: 1535-1537.

Brannigan, P.G. and J.B. McQuitty. 1971. The influence of ventilation on distribution and dispersal of atmospheric gaseous contaminants. Can. Agric. Eng., 13 (2): 69-75.

Brody, S. 1945. Bioenergetics and Growth. Reinhold Publishing Corp. Now published by Hafner Publishing Co., Inc. New York, New York. 1968.

Brouwer, E. 1965. Report of sub-committee on constants and factors. In: K.L. Blaxter (Ed.), Energy Metabolism. Academic Press, London. pp. 441-443.

Bruce, J.M. 1981. Ventilation and temperature control criteria for pigs. In: J.A. Clark (Ed.), Environmental Aspects of Housing for Animal Production. Butterworths, London. pp. 197-216.

Bullis, K.L., G.H. Snoeyenbos and H. van Rockel. 1950. A keratoconjunctivitis in chickens. Poult. Sci., 29: 386-389. (Cited by Lampman (1982)).

Burlacu, G. and M. Baltac. 1971. Efficiency of the utilization of the energy of food in laying hens. J. Agric. Sci., Camb., 77: 405-411.

Burlacu, G., I. Dumitra and M. Baltac. 1970a. Efficiency of the utilization of the energy of casein in fowls. J. Agric. Sci., Camb., 75: 207-211.

Burlacu, G., M. Baltac and M. Perasehiv. 1970b. Efficiency of food energy utilization in growing chickens. In: A. Schurch and C. Wenk (Eds.), Energy Metabolism of Farm Animals. Juris Verlag, Zurich. pp. 209-212.

Byerly, T.C. 1960. Goals of engineering research on poultry housing. Trans. Amer. Soc. Agric. Eng., 9 (1): 566-567.

Carlson, H.C. and G.R. Whenham. 1967. Coliform bacteria in chicken broiler house dust and their possible relationship to coli-septicemia. Avian Diseases, 12: 297-302.

Cena, K. 1973. Radiative heat loss from animals and man. In: J.L. Monteith and L.E. Mount (Eds.), Heat Loss from Animals and Man: Assessment and Control. Butterworths, London. pp. 33-58.

Champion, L.R. and H.C. Zindel. 1968. Performance of layers in single and multiple bird cages. Poult. Sci., 47: 1130-1135.

Charles, D.R. and C.G. Payne. 1966a. The influence of graded levels of atmospheric ammonia on chickens. I. Effects on respiration and on the performance of broilers and replacement growing stock. Brit. Poult. Sci., 7 (3): 177-187.

Charles, D.R. and C.G. Payne. 1966b. The influence of graded levels of atmospheric ammonia on chickens. II. Effects on the performance of laying hens. Brit. Poult. Sci., 7 (3): 189-198.

Charles, D.R. and P.G. Spencer. 1976. The Climatic Environment of Poultry Houses. Bull. 212, Ministry of Agriculture, Fisheries and Food, London, U.K.

Christmas, R.B., C.R. Douglas, L.W. Kalch and R.H. Harms. 1982. The effect of low protein pullet growing diets on performance of laying hens housed in the fall. Poult. Sci., 63: 82.

Clark, P.C. 1982. Heat and Moisture Loads in Commercial Swine Feeder Barns in Alberta. Unpublished M.Sc. Thesis, Department of Agricultural Engineering, University of Alberta, Edmonton, Alta.

Curtis, S.E. 1981. Environmental Management in Animal Agriculture. Animal Environment Services, Mahonnet, Illinois.

Davis, W.M. and A.B. Watts. 1955. The effect of ration treatments during the various stages of the chickens' life upon the subsequent performance of laying hens. Poult. Sci., 34: 1231.

Deaton, J.W. and J.H. Quisenberry. 1963. Effects of caloric restriction during the growing period on the performance of egg-type replacement stock. Poult. Sci., 42: 608.

Deaton, J.W., F.N. Reece and C.W. Bouchilton. 1969. Heat and moisture production of broilers. 2. Winter conditions. Poultry Sci., 55: 1579-1582.

Deighton, T. 1939. A study on the metabolism of fowl. I. A calorimeter for the direct determination of the metabolism of fowls. J. Agric. Sci., Camb., 29: 431-451.

Deighton, T and J.C.D. Hutchinson. 1940a. Studies on the metabolism of fowl. II. The effect of activity on metabolism. J. Agric. Sci., Camb., 30: 141-157.

Deighton, T and J.C.D. Hutchinson. 1940b. Studies on the metabolism of fowl. III. The determination of the comparative net energy of Sussex ground oats and white maize meal for fattening cockerels. J. Agric. Sci., Camb., 30: 463-484.

Denbow, D.B. and W.J. Kuenzel. 1981. Gaseous metabolism of Leghorns and broilers during early growth: existence rate. Poult. Sci., 60: 1340-1343.

DeShazer, J.A. and F.B. Mather. 1981. Initial heat losses of pullets grouped at different cage densities. Paper No. 81-4545, Amer. Soc. Agric. Eng., St. Joseph, MI.

DeShazer, J.A., F.B. Mather and K.A. Jordan. 1969. The dynamic heat loss variations of the laying hen. Paper

No. 69-527, Amer. Soc. Agric. Eng., St. Joseph, MI.

DeShazer, J.A., K.A. Jordan and C.W. Suggs. 1970. Effect of acclimation on partitioning of heat loss by the laying hens. Trans. Amer. Soc. Agric. Eng., 13(1): 82-84. (Cited by Scott et al. (1983)).

DeShazer, J.A., J.J.R. Feddes and J.B. McQuitty. 1982. Comparison of methods for measuring conductive heat losses from livestock buildings. Can. Agric. Eng., 24(1): 1-4.

Dick, J.B. and P.T. Loader. 1960. Temperatures and humidities in pig houses. A study of internal climate in relation to heat and moisture production. National Building Studies, Research Paper No. 29, Department of Scientific and Industrial Research, London.

Donham, K.J. and K.W. Gustafson. 1981. Human health hazards in livestock confinement. Paper presented at Symposium on Agricultural Respiratory Hazards, American Governmental Industrial Hygienists, Kansas City, Mo.

Donham, K.J., M. Rubino, T.D. Thedell and J. Kammermeyer. 1977. Potential health hazards to agricultural workers in swine confinement buildings. J. Occup. Med., 19(6): 383-387.

Donham, K.J., L.W. Knapp, R. Monson and K. Gustaffson. 1982. Acute toxic exposure to gases from liquid manure. J. Occup. Med., 24: 142-145.

Douglas, C.R. and R.H. Harms. 1982. The influence of low protein grower diets on spring housed pullets. Poult. Sci., 63: 302.

Drury, L.N. 1970. Filtered-air positive-pressure ventilation systems for preventing airborne diseases in poultry houses. Paper No. 70-914, Amer. Soc. Agric. Eng., St. Joseph, Michigan.

Dukes, H.H. 1937. Studies on the energy metabolism of the hen. J. Nutr., 14: 341-353. (Cited by van Kampen (1974)).

Dukes, H.H. 1947. The Physiology of Domestic Animals. 6th Ed. Comstock Publ., Ithaca, New York.

Emmans, G.C. 1971. Stocking practices and performance in commercial layer flocks. World Poult. Sci. J., 27: 356-361.

Emmans, G.C. and P. Dun. 1973. Gleadthorpe Experimental Husbandry Farm. Poultry Booklet No. 1. London, Ministry of Agriculture, Fisheries and Food.

Esmay, M.L. 1979. Principles of Animal Environment. AVI Publishing Company Inc., Westport, Connecticut.

Farrell, D.J. 1974. General principles and assumptions of calorimetry. In: T.R. Morris and B.M. Freeman (Eds.), Energy Requirements of Poultry. British Poultry Science Ltd, Edinburgh. pp. 1-24.

Farrell, D.J. and T.R. Walker. 1973. The interrelationship between vitamin A status, parasitism, and energy metabolism in growing chickens. Proc. 6th Symp. on Energy Metabolism, Stuttgart.

Feddes, J.J.R. and J.B. McQuitty. 1973. Effects of beef housing systems on gaseous contaminants removed by ventilation. Can. Agric. Eng., 15(2): 119-123.

Feddes, J.J.R. and J.B. McQuitty. 1977. Data acquisition system for measuring environmental variables within confinement animal units. Can. Agric. Eng., 19(2): 75-77.

Feddes, J.J.R. and J.B. McQuitty. 1980. Design of an air-speed sensor system. Can. Agric. Eng., 22(1): 97-99.

Feddes, J.J.R. and J.B. McQuitty. 1981. Environmental monitoring in animal housing. Paper No. PNW 81-403, Amer. Soc. Agric. Eng., St. Joseph, Michigan.

Feddes, J.J.R., J.J. Leonard and J.B. McQuitty. 1984a. Broiler heat and moisture production under commercial conditions. Can. Agric. Eng., 26(1): 57-64.

Feddes, J.J.R., J.B. McQuitty and P.C. Clark. 1984b. Laying hen heat and moisture production under commercial conditions. Paper No. 84-404, Can. Soc. Agric. Eng., Ottawa, Ontario.

Feldkamp, J.F. and A.W. Adams. 1973. Effects of rearing relationships and bird density on performance and fearfulness of White Leghorn Layers. Poult. Sci., 61: 239-243.

Flatt, W.P. 1969. Methods of Calorimetry (B) Indirect. In: D.P. Cuthbertson (Ed.), Nutrition of Animals of Agricultural Importance. Pergammon Press, London. pp. 491-522.

Foss, D.C. and L.B. Carew. 1974. Effects of dietary energy and hen density on performance of caged Leghorn pullets. Poult. Sci., 37: 215-223.

Freeman, B.M. 1964. The emergence of the homeothermic-metabolic response in the fowl. Comp. Biochem. Physiol., 13: 413-422.

Froning, G.N. and B.A.M. Sackett. 1984. Effect of gaseous pre-slaughter environment on chicken broiler meat quality. Poult. Sci., 63 (Suppl. No. 1):103 (Abstract).

Gaspar, E., P.H. Sommelwitz, C.R. Richards and M.S. Cover. 1961. The influence of atmospheric ammonia on blood haemoglobin levels. Amer. Soc. Anim. Prod. North Atlantic Section, Proc. 3: 68-74.

Gowe, R.S. 1956. Environment and poultry breeding problems. A comparison of the egg production of seven S.C. White Leghorn strains housed in laying batteries and pen floors. Poult. Sci., 35: 430-435.

Gowe, R.S., J.H. Strain, R.D. Crawford, A.T. Hill, S.B. Slen and W.F. Mountain. 1964. Restricted feeding of growing pullets. II. The effect on costs, returns and profits. Poult. Sci., 44: 717.

Graves, H.B. 1982. Behavioral responses of poultry (chickens) to management systems. In: W. Woods (Ed.), Proc. of the Symp. on Management of Food Producing Animals, Vol. I. Animal Sciences Dept., Purdue University, IN. pp. 122-138.

Grimbergen, A.H.M. 1970. The energy requirement for maintenance and production of laying hens. Neth. J. Agric. Sci., 18: 195-206.

Grub, W.C., C.A. Rollo and J.R. Howes. 1965. Dust problems in poultry environment. Trans. Amer. Soc. Agric. Eng., 8(3): 338-339, 352.

Guo, L.S. and J.D. Summers. 1970. Influence of a thiamine deficiency on basal metabolic rate, specific dynamic effect, and the efficiency of energy utilization. Poult. Sci., 49: 1225-1231.

Harry, E.G. and L.A. Hemsley. 1964. Factors influencing the survival of coliforms in dust of deep litter houses. Vet. Record 76: 863-867.

Harms, R.H. 1982. Feed restrictions of poultry. In: W. Woods (Ed.), Proc. of the Symp. on Management of Food Producing Animals, Vol. 1. Animal Sciences Dept., Purdue University, Indiana. pp. 293-304.

Harrison, P.C. and H.V. Biellier. 1969. Physiological response of domestic fowl to abrupt changes of ambient air temperature. Poult. Sci., 48: 1034-1045.

Helbacka, N.V., J.L. Casterline, Jr. and C.J. Smith. 1963. The effect of high carbon dioxide atmosphere on the laying hen. Poult. Sci., 42: 1082-1084, 1095.

Hohls, H.W. 1954. Rhythms of the hourly heat-production of hens during the day. 10th World Poult. Congr., Edinburgh. pp. 178-181. (Cited by Balnave (1974)).

Honey, H.F. and J.B. McQuitty. 1976. Dust in the animal environment. Res. Bull. 76-2, Department of Agricultural Engineering, University of Alberta, Edmonton, Alberta. 66 pp. 101 ref.

Hutchinson, J.C.D. 1954. Heat regulation in birds. In: J.

Hammond (Ed.), Progress in the Physiology of Farm Animals, Vol. 1. Butterworths, London. pp. 299-362.

Hutt, F.B. 1949. Genetics of the fowl. McGraw-Hill, New York. (Cited by Graves (1982)).

Huxley, T.H. 1868. On the animals which are most nearly intermediate between the birds and the reptiles. Ann. and Mag. Nat. Hist., 2:66. (Cited by Graves (1982)).

Hy-Line Commercial Management Guide. 1982. Variety W-77. A publication of Hy-Line Indian River Co., Johnston, Iowa 50131.

Jackson, N. 1972. Effect of restricting the energy intake of the laying hen, directly and dilution of the diet, on egg production and the efficiency of energy utilization. J. Sci. Fd. Agric., 23: 413-428.

Johnson, D. 1981. Summary information about livestock manure pit fatalities. Unpublished data, Department of Agricultural Engineering, North Dakota State University, Fargo, ND 58015. (Cited by McQuitty and Feddes (1982)).

Johnson, H.S. and H.C. Zindel. 1961. Comparison between pullets in cages, slatted floors, and litter floor. Poult. Sci., 40: 1418.

Jorgenson, R. 1983. Fan Engineering. Eighth Ed., Buffalo Forge Company, Buffalo, N.Y.

Jurajda, V. and B. Klimes. 1970. Presence and survival of Marek's disease agent in dust. Avian Diseases, 14: 188-190.

King, J.R. and D.S. Farner. 1961. Energy metabolism, thermoregulation and body temperature. In: A.J. Marshall (Ed.), Biology and Comparative Physiology of Birds, vol. II. Academic Press, New York. pp. 215-288.

Kleiber, M. 1945. Dietary deficiencies and energy metabolism. Nutr. Abstr. Rev., 15: 212-222.

Kleiber, M. 1975. The Fire of Life. Robert E. Kreiger Publ. Co., Huntington, New York.

Lampman, W.P. 1982. Analysis of dust particles and their influence in a livestock environment. Bull. 1-1982, Department of Agricultural Engineering, University of Saskatchewan, Saskatoon, SK. 69 pp. 90 ref.

Lampman, C.E., J.E. Dixon, C.F. Petersen and R.E. Black. 1967. Environmental control for poultry housing. Res. Bull. 456. Idaho Agricultural Experiment Station, Moscow, Idaho. (Cited by Lampman (1982)).

Lasiewski, R.C., A.L. Acosta and M.H. Bernstein. 1966. Evaporative water loss in birds. I. Characteristics of the open flow method of determination and their relation to estimates of thermoregulatory ability. Comp. Biochem. Physiol., 19: 1034-1045.

Leonard, J.J., J.J.R. Feddes and J.B. McQuitty. 1984a. Measurement of ventilation rates using a tracer gas. Can. Agric. Eng., 26(1): 72-79.

Leonard, J.J., J.J.R. Feddes and J.B. McQuitty. 1984b. Air quality in commercial broiler housing. Can. Agric. Eng., 26(1): 65-71.

Lillie, R.J. 1970. Air pollutants affecting the performance of domestic animals. A literature review. Agriculture Handbook No. 380. Agricultural Research Service. U.S.D.A., Washington, D.C.

Longhouse, A.D., H. Ota and W. Ashby. 1960. Heat and moisture design data for poultry housing. Trans. of the Amer. Soc. of Agric. Eng. 9(2): 567-576.

Longhouse, A.D., C.S. Shaffner and G.O. Bressler. 1963. Poultry housing - basic data useful for design purposes in the northeast United States. W. Va. Agr. Expt. Sta. Bul. 486T. (Cited by Lampman (1982)).

Longhouse, A.D., H. Ota, R.E. Emerson and J.O. Heishman. 1968. Heat and moisture design data for broiler houses. Trans. Amer. Soc. Agric. Eng., 2(5): 694-700.

Lowery, D.C., I.M. Lerner and L.W. Taylor. 1956. Intra flock genetic merit under floor and cage management. Poult. Sci., 35: 1034-1043.

Ludington, D.C., A.T. Sobel and A.G. Hashimoto. 1969. Odors and gases liberated from diluted and undiluted chicken manure. Paper No. 69-426, Amer. Soc. Agric. Eng., St. Joseph, MI.

McAllister, J.S.V. and J.B. McQuitty. 1965. Release of gases from slurry. Rec. Agric. Res. Minist. Agric., N. Ire., 14, Part 2: 73-78.

McLean, J.A. 1974. Loss of heat by evaporation. In: J.L. Monteith and L.E. Mount (Eds.), Heat Loss from Animals and Man. Butterworth Group, London. pp. 19-31.

McQuitty, J.B. and J.J.R. Feddes. 1982. Manure gases and the animal environment. Paper presented at Joint Session, CSAE/CSA/CSAS, AIC Annual Conference, Vancouver, B.C.

McQuitty, J.B., J.J.R. Feddes and J.J. Leonard. 1984. A comparison of air quality in three commercial laying operations. Paper No. PNR-84-302, Amer. Soc. of Agric. Eng., St. Joseph, Michigan.

Marsden, A., E. Wethli, N. Kinread and T.R. Morris. 1973. The effect of environmental temperature on feed intake of laying hens. World Poult. Sci. J., 29: 286.

Midwest Plan Service. 1983. Structures and Environment Handbook. MWPS-1, Midwest Plan Service, Ames, Iowa.

Milby, T.T. and D.H. Sherwood. 1956. The influence of feed intake during the growth period on the subsequent performance of laying hens. Poult. Sci., 35: 863.

Miller, W.S. 1974. The determination of metabolisable energy. In: T.R. Morris and B.M. Freeman (Eds.), Energy Requirements of Poultry. British Poultry Science Ltd, Edinburgh. pp. 91-111.

Miller, M.M. and J.H. Quisenberry. 1959. Factors affecting feed efficiency for egg production in selected strains of caged layers. Poult. Sci., 38: 757-766.

Miller, P.C. and M.L. Sunde. 1975. Combinations of restricted feeding, lighting and energy levels on performance of growing pullets and subsequent layer performance. Poult. Sci., 54: 1631.

Mitchell, B.W. 1983. Instrumentation and Measurement for

Environmental Scientists. Published by Amer. Soc. Agric. Eng., St. Joseph, MI.

Mitchell, H.H. and W.T. Haines. 1927. The basal metabolism of mature chickens and the net-energy value of corn. J. Agric. Res., 34: 927-943.

Mitchell, H.H. and M.A.R. Kelley. 1933. Estimated data on the energy, gaseous, water metabolism of poultry for use in planning the ventilation of poultry houses. J. Agric. Res., 47: 735-747. (Cited by Stewart and Hinkle (1959)).

Mitchell, H.H., L.E. Card and W.T. Haines. 1927. The effect of age, sex and castration on the basal heat production of chickens. J. Agric. Res., 34: 945-960.

Mitchell, D., A.R. Atkins and C.H. Wyndham. 1972. Mathematical and physical models of thermoregulation. In: J. Bligh and R. Moore (Eds.), Essays on Temperature Regulation. American Elsevier Publ., New York. pp. 37-54.

Morris, T.R. 1962. Effect of photoperiod from hatch to 500 days on pullets' egglaying performance. World Poult. Sci. J., 23:326.

Morris, J.R. 1967. Light requirements of the fowl. In: T.C. Carter (Ed.), Environmental Control in Poultry Production. Oliver and Boyd, Edinburgh and London.

Morris, T.R. 1977. Effect of environmental conditions on egglaying in clutches. Brit. Poult. Sci., 18: 397.

Morris, T.R. and S. Fox. 1960. Effect of photoperiod during rearing of broiler breeder pullets. Brit. Poult. Sci., 1: 25.

Moulsley, L.J. 1977. A comparison between winter and summer concentrations of ammonia and carbon dioxide in the atmosphere of two broiler houses. Sectional Note no. SN/EN/23/10003, National Institute of Agricultural Engineering, Silsoe, England.

Mount, L.E. 1973. The concept of thermal neutrality. In: J.L. Monteith and L.E. Mount (Eds.), Heat Loss from Animals and Man. Butterworths, London. pp. 2-73.

Mount, L.E. 1979. Adaptation to Thermal Environment. Edward Arnold Ltd, London. pp. 14-74.

Munroe, J.A., R.J. Milne, D. Hodgkinson and E.M. Barber. 1982. Free-stall dairy cattle housing. Publ. 1715/E, Agriculture Canada, Ottawa, Ontario, Canada.

Murray, D.B. and W.S. Mitchell. 1980. Outline of the poultry industry in Canada. World Poult. Sci. J., 38: 175-18[illegible]

Nagaraja, K.V., D.A. Emery, K.A. Jordan, J.A. Newman and B.S. Pomeroy. 1983. Scanning electron microscopic studies of adverse effects of ammonia on tracheal tissues of turkeys. Am. J. Vet. Res., 44(8): 1530-1536.

Nordstrom, G.A. and J.B. McQuitty. 1976. Manure gases in the animal environment - a literature review (with particular reference to cattle housing). Res. Bull. 76-1, Dept. of Agric. Eng., University of Alberta, Edmonton. 80 pp. 115 ref.

Noren, O., S. Skarp and G. Aniansson. 1967. Manure gas problem. Circular No. 20, Swedish Institute of Agric. Eng.

(JTI), Uppsala, Sweden.

Novikoff, M. and J. Biely. 1945. Observations on two methods of feeding chickens from one day old to twelve months of age. Poult. Sci., 24: 245.

Olson, L.L., J.A. DeShazer and F.B. Mather. 1974. Convective, radiative and evaporative heat losses of White Leghorn layers as affected by bird density per cage. Trans. Amer. Soc. Agric. Eng., 17(5): 960-964 and 967. (Cited by Feddes et al. (1984b)).

O'Neill, S.J.B., D. Balnave and N. Jackson. 1970. Calorimetric studies on the effect of feathering and environmental temperature on heat production of the cockerel. Abstr. 14th World Poult. Sci. Congr., Madrid, Section 4, 918.

O'Neill, S.J.B., D. Balnave and N. Jackson. 1971. The influence of feathering and environmental temperature on the heat production and efficiency of utilization of metabolizable energy by the mature cockerel. J. Agric. Sci. Camb., 77: 293-305.

Osbern, L.N., R.O. Crapo and K.J. Donham. 1981. Dung lung: a report on toxic exposure to liquid manure. Ann. Inter. Med., 95: 312-314.

Ostrom, J.H. 1976. Some hypothetical anatomical stages in the evolution of avian flight. Smithsonian Contributions to Paleobiology, 27: 1. (Cited by Graves (1982)).

Ota, H. and E.H. McNally. 1961. Poultry respiration calorimeter studies of laying hens. U.S.D.A. ARS 42-43.

Washington, D.C.

Peterson, C. 1970. Efficiency of protein and fat deposition in growing chickens determined by respiration experiments. In: A. Schurch and C. Wenk (Eds.), Energy Metabolism of Farm Animals. Juris Verlag, Zurich. pp. 205-208.

Petrov, G. 1966. Effect of increased concentration of ammonia, hydrogen sulphide and carbon dioxide on laying hens. (Cited in Bibl. Farm Bldg. Res., 1967 Supplement, Abstr. No. 292.)

Prince, R.P., T.N. Fredrickson and J.H. Carrozza. 1971. Aerobiological transmission of Marek's disease. Paper No. 71-426, Amer. Soc. Agric. Eng., St. Joseph, MI.

Pullar, J.D. 1957. Energy expenditure in livestock. Advt. Sci., London, No. 53, 491-493.

Pullar, J.D. 1969. Methods of calorimetry (A) Direct. In: D.P. Cuthbertson (Ed), Nutrition of Animals of Agricultural Importance. Pergamon Press, London. pp. 471-490.

Quisenberry, J.H. and J.W. Bradley. 1964. Effects of bird density on performance of egg production stock. Poult. Sci., 43: 1354.

Randall, W.C. 1943. Factors influencing the temperature regulation of birds. Am. J. Physiol., 139: 56.

Reece, F.N. 1979. The effect of ammonia on the performance of broiler chickens. Paper No. 79-4004, Amer. Soc. Agric. Eng., St. Joseph, MI.

Reece, F.N. and B.D. Lott. 1982. Optimizing poultry house design for broiler chickens. Poult. Sci., 61(1): 25.

Reece, F.N., J.W. Deaton and L.F. Kubena. 1972. Effects of high temperature and humidity on heat prostration of broiler chickens. Poult. Sci., 51(6): 2021.

Reece, F.N., B.D. Lott and J.W. Deaton. 1981. Low concentrations of ammonia during brooding decrease broiler weight. Poult. Sci., 50(5): 937-940.

Richards, S.A. 1976. Behavioural temperature regulation in the fowl. J. Physiol. (London), 258: 1228-1238.

Richardson, H.B. 1929. The respiratory quotient. Physiol. Rev., 9: 61-125. (Cited by Farrell (1974)).

Riskowski, G.L., J.A. DeShazer and F.B. Mather. 1977. Heat losses of White Leghorn laying hens as affected by intermittent lighting schedules. Trans. Amer. Soc. Agric. Eng., 20(4): 727-731. (Cited by Feddes et al. (1984b)).

Robertson, A.M. and H. Galbraith. 1971. Effect of ventilation on the gas concentration in part-slatted piggery. Scottish Farm Bldgs. Investigation Unit, Aberdeen. No. 1, pp. 17-28.

Roller, W.L. and A.C. Dale. 1963. Heat losses from Leghorn layers at warm temperatures. Trans. Amer. Soc. Agric. Eng., 6(2): 136-139.

Romer, A.S. 1966. Vertebrate Paleontology (3rd Ed.). University of Chicago Press, Chicago.

Romijn, C. 1954. Development of heat regulation in the chick. Proc., 10th World Poult. Congr., British Poultry Science Ltd, Edinburgh, pp. 181-184.

Romijn, C. and W. Lokhorst. 1961. Climate and Poultry. Heat regulation in fowl. Tijdschr. Diergeneesk., 86: 153-172.

Romijn, C. and W. Lokhorst. 1966. Heat regulation and energy metabolism in the domestic fowl. In: C. Horton-Smith and E.C. Amoroso (Eds.), Physiology of the Domestic Fowl. Oliver and Boyd, Edinburgh. pp. 211-227.

Romijn, C. and E.L. Vreugdenhil. 1969. Energy balance and heat regulation in the White Leghorn fowl. Neth. J. Vet. Sci., 2: 32-59.

Rose, R.J. and J.L. Sell. 1969. Comparison of rearing and laying performance. Poult. Sci., 48: 1863.

Ruszler, P.L. and J.H. Quisenberry. 1970. Responses of caged layers to population size and bird density stresses. Poult. Sci., 49: 1433.

Sainsbury, D.W.B. 1980. Poultry Health and Management. Granada Publishing Ltd., London.

Scott, N.R., J.A. DeShazer and W.L. Roller. 1983. Effects of the thermal and gaseous environment on livestock. In: M.A. Hellickson and J.N. Walker (Eds.), Ventilation of Agricultural Structures, Amer. Soc. Agric. Eng., St. Joseph, Michigan. Ch. 7.

Sefton, A.E. 1976. The interaction of cage size, cage level, social density, fearfulness and production of S.C. White Leghorns. Poult. Sci., 55: 1922-1926.

Shannon, D.W.F. and W.O. Brown. 1969a. Calorimetric studies on the effect of dietary energy source and environmental temperature on the metabolic efficiency of energy utilization by mature Light Sussex cockerels. J. Agric. Sci., Camb., 72: 479-489.

Shannon, D.W.F. and W.O. Brown. 1969b. The period of adaptation of the fasting metabolic rate of the common fowl to an increase in environmental temperature from 22°C to 28°C. Brit. Poult. Sci., 10: 13-18.

Shannon, D.W.F. and W.O. Brown. 1970. Calorimetric estimate of the efficiency of utilization of dietary energy by the growing cockerel. Brit. Poult. Sci., 11: 1-6.

Shaver Commercial Management Guide. 1982. Starcross 288. Publication No. T-11-Y, Shaver Poultry Breeding Farms Ltd, Cambridge, Ontario.

Sherwood, D.H. and T.T. Milby. 1954. Restricted versus full-feeding for growing pullets. Poult. Sci., 33: 1080.

Siegel, H.S. and L.N. Drury. 1968. Physiological responses of chickens to variations in air temperature and velocity. Poult. Sci., 47: 1120-1127.

Siopes, T.D. 1982. Specifications for environmental control in poultry - lighting. In: W. Woods (Ed.), Proc. of the Symp. on Management of Food Producing Animals, Vol. I. Animal Sciences Department, Purdue University, IN. pp. 271-292.

Smith, C.V. 1972. Some environmental problems of livestock housing. Technical Note No. 122, Secretariat of World Meteorological Organization, Geneva, Switzerland.

Smith, W.K. 1975. Environmental physiology in relation to egg production. I. Concepts of energy management and fundamentals of the thermal design of buildings in the cool half of the year. Information Series No. 1, Poultry Research Centre, Massey University, New Zealand. pp. 6-8.

Smith, A.J. and J. Oliver. 1972a. Some nutritional problems associated with egg production at high environmental temperatures. I. The effect of environmental temperature and rationing treatments on the productivity of pullets fed on diets of differing energy content. Rhod. J. Agric. Res., 10: 3-21.

Smith, A.J. and J. Oliver. 1972b. Some nutritional problems associated with egg production at high environmental temperatures. IV. The effect of prolonged exposure to high environmental temperatures on the productivity of pullets fed on high energy diets. Rhod. J. Agric. Res., 10: 43-60.

Starr, J.R. 1981. Climate and the need for housing. In: J.A. Clark (Ed.), Environmental Aspects of Housing for Animal Production. Butterworths, London. pp. 19-36.

Stewart, R.E. and C.N. Hinkle. 1959. Environmental requirements for poultry shelter design. Trans. Amer. Soc. Agric. Eng., 9(2): 532-535.

Strain, J.H., R.S. Gowe, R.D. Crawford, A.T. Hill, S.B. Slen and W.F. Mountain. 1965. Restricted feeding of growing pullets. I. The effect on the performance traits of egg production stock. Poult. Sci., 44: 701.

Sturkie, P.D. 1965. Avian Physiology, 2nd Ed. Cornell University Press. pp. 200.

Sykes, A.H. 1970. Resting oxygen consumption of chicks infected with intestinal coccidiosis. Res. Vet. Sci., 11: 489-490.

Taiganides, E.P. and R.K. White. 1969. The menace of noxious gases in animal units. Trans. Amer. Soc. Agric. Eng., 12: 359-362, 367.

Tasaki, I. and H. Sakurai. 1964. Studies on the energy metabolism in the fowl. II. Metabolism in fasting condition. Jap. J. Zootech. Sci., 35: 18-25.

Tasaki, I. and H. Sakurai. 1965. Studies on the energy metabolism in the fowl. III. On energy requirement for maintenance of cross-bred cockerels. Jap. J. Zootech. Sci., 36: 515-521.

Tasaki, I. and Y. Sasa. 1970. Energy metabolism in laying hens. In: A. Schurch and C. Wenk (Eds.), Energy Metabolism of Farm Animals. Juris Druck Verlag, Zurich. pp. 197-200.

Teter, N.C. and J.A. DeShazer. 1976. Animal performance models. Paper No. 76-5013, Amer. Soc. Agric. Eng., St. Joseph, Michigan.

Thompson, P.D. 1974. Discussion on the influence of environmental factors on health of livestock. In: Proceedings of the International Livestock Environment Symposium, Amer. Soc. Agric. Eng., St. Joseph, Michigan.

Turnbull, J.E. and N.A. Bird. 1981. Confinement swine housing. Publ. 1451, Agriculture Canada, Ottawa, Canada.

van Es, A.J.H., L. Vik-Mo, H. Janssen, A. Bosch, E. Spreewenburg, J.E. Vogt and H.J. Nijkamp. 1970. Balance trials with laying hens. In: A. Schurch and C. Wenk (Eds.), Energy Metabolism of Farm Animals. Juris Druck Verlag, Zurich. pp. 201-204.

van Handel-Hruska, J.M., T.N. Wegner and J.O. Nordstrom. 1977. Proc. Fedn. Amer. Socs. Exp. Biol. 36: 524. (Cited by van Kampen (1981)).

van Kampen, M. 1974. Physical factors affecting energy expenditure. In: T.R. Morris and B.M. Freeman (Eds.), Energy Requirements of Poultry. British Poultry Science Ltd, Edinburgh. pp. 47-59.

van Kampen, M. 1976. Evaporative temperature regulation in birds. In: H.D. Johnson (Ed.), Progress in Biometerology. The effect of temperature on animals. Swets and Zeitlinger B.V., Amsterdam. pp. 158-166. (Cited by Scott et al. (1983)).

van Kampen, M. 1981. Thermal influences on poultry. In: J.A. Clark (Ed.), Environmental Aspects of Housing for Animal Production. Butterworths, London. pp. 131-148.

van Kampen, M. and C. Romijn. 1970. Energy balance and heat regulation in the White Leghorn fowl. In: A. Schurch and C. Wenk (Eds.), Energy Metabolism of Farm Animals. Juris Druck Verlag, Zurich. pp. 213-216.

Valentine, H. 1964. A study of the effect of different ventilation rates on the ammonia concentration in the atmosphere of broiler houses. Brit. Poult. Sci., 5(2):

149-159.

Walter, E.D. and J.R. Atkins. 1961. Performance of laying hens subjected to restricted feeding during rearing and laying periods. Poult. Sci., 40: 345.

Waring, J.J. and W.O. Brown. 1965. A respiration chamber for the study of energy utilization for maintenance and production in the laying hen. J. Agric. Sci., Camb., 65: 139-146.

Waring, J.J. and W.O. Brown. 1967. Calorimetric studies on the utilization of the dietary energy by the laying White Leghorn hen in relation to plane of nutrition and environmental temperature. J. Agric. Sci., Camb., 68: 149-155.

Wathes, C.M. and J.A. Clark. 1978. Sensible heat transfer from the fowl: thermal resistance of the pelt. Brit. Poult. Sci., 22: 175-183.

Wells, R.G. 1971. Studies on stocking arrangement for caged layers. World Poult. Sci. J., 27: 361-366.

Wildey, H.E. 1982. Cages vs. floor systems for commercial layers. In: W. Woods (Ed.), Proc. of Symp. on the Management of Food Producing Animals, Vol. I. Animal Sciences Department, Purdue University, IN. pp. 231-251.

Winchell, W. 1982. Poultry housing facilities. Alberta Agriculture, Edmonton, Alberta. pp. 16-22.

Young, B.A. 1979. Effects of low temperature on cattle production. Paper No. 79-4007, Amer. Soc. Agric. Eng., St. Joseph, Michigan.

8. Appendix A - Conversion Equations and Instrumentation

The equations used in Fortran program to convert the raw voltage data to engineering units are presented here:

1. Thermistor-based Measurements:

   a. Thermistor constant-current circuit;

   $$R = D/I - L(RES)$$

   where R = sensor resistance, ohms

   D = output to data logger, volts

   I = constant current of 0.5 mA

   L = length of thermistor lead wire, m, and

   RES = resistance of wire per 30.5-m-length

   b. Temperature determination from resistance;

   $$1/T = AX^3 + BX + C$$

   where T = temperature, °C

   X = ln R

   A = regression coefficient, $.209099055/10^6$

   B = regression coefficient, $.275851225/10^3$

   C = regression coefficient, $.137958851/10^2$

2. Dewpoint Measurement:

   Dewpoint determination - (dewpoint hygrometer);

   $$DP = 1.36D - 28.6$$

   where DP = dewpoint, °C

   D = output to data logger, volts

   AA = regression coefficient, 1.36, and

   BB = regression coefficient, 28.6

3. Air Quality Measurements:

a. Carbon Dioxide;

$$C = AK^2 + BK + C$$

where C = CO_2 concentration, ppm

A = regression coefficient, 0.038

K = output voltage, volts

B = regression coefficient, 0.4132

C = regression coefficient, 0.0424

b. Ammonia;

$$N = AD/2000$$

where N = NH_3 concentration, ppm

A = regression coefficient, 140.0

D = output voltage, volts

c. Hydrogen Sulphide;

$$H = 2.52\ D/1000$$

where H = H_2S concentration, ppb

4. Water Flow Measurements:

Doppler calibration; $F = AX + B$

where F = water flow, m/s

A = regression coefficient, 0.315

X = Doppler reading, m/s

B = regression coefficient, -0.019

5. Anemometer calibrations:

Thermistor: $Y = 0.1444 + 0.7065X$

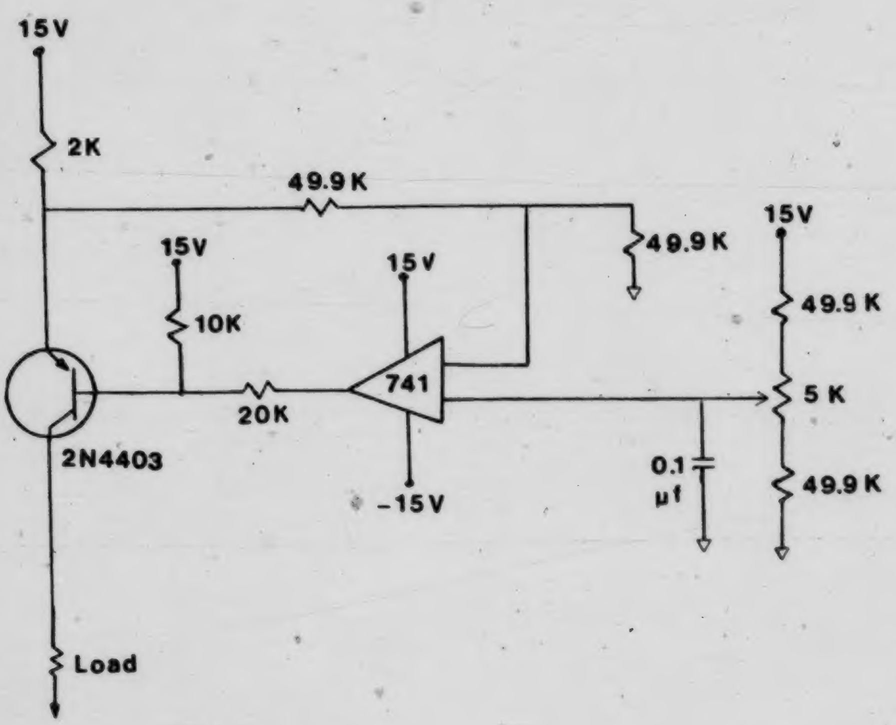
Hot-wire: $Y = -0.088 + 0.9666X$

where Y = actual air velocity, m/s

X = observed air velocity, m/s

Constant Current Circuit

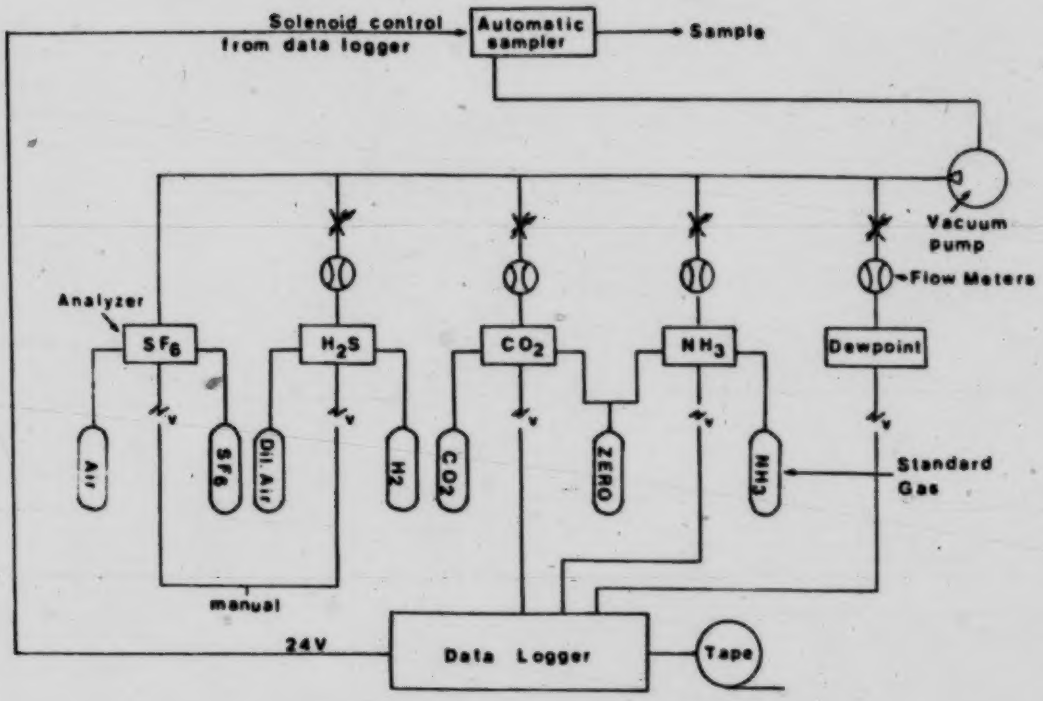
(0.5 mA)



2N4403 - pnp transistor

741 - Operational amplifier

Figure A1. Constant current circuit diagram.



Note : Dust analyzer has separate valves and pump.
Output is to separate paper tape.

Figure A2. Schematic diagram of air sampling instrumentation.

9. Appendix B - Data Output

The following columns of data were collected for a 24-hour period during the second run for Barn B. The abbreviated symbols on top of each are explained as follows:

T = Time elapsed in hours with the starting time in the first column.

DH = The difference in enthalpy of the inside and outside air, kJ/kg dry air.

WAT = Amount of moisture removed by the fans, (kg/h).

HEAT = Total heat removed by the fans, MJ/h.

PROD = Total heat produced by the birds, MJ/h.

BLD = Conductive heat loss, kJ/(h.bird).

VH = HEAT per bird, kJ/(h.bird).

PRD = PROD on a bird basis, kJ/(h.bird).

T	DH	WAT	HEAT	PROD	BLD	VH	PRD
11	40.8	24.1	148.6	172.7	1.8	10.9	12.8
12	37.1	35.3	222.1	245.9	1.7	16.2	17.8
13	34.4	33.6	210.4	233.1	1.7	15.4	16.9
14	34.5	32.0	207.8	230.5	1.7	15.2	16.8
15	35.1	31.8	213.9	236.7	1.7	15.6	17.3
16	35.0	31.1	211.8	233.6	1.6	15.5	17.0
17	35.6	26.6	174.5	196.1	1.6	12.8	14.4
18	36.8	17.8	113.7	135.3	1.6	8.3	10.0
19	36.8	17.9	118.2	140.5	1.6	8.6	10.3

20	36.9	17.6	117.2	139.7	1.6	8.6	10.2
21	35.9	23.7	164.1	186.7	1.6	12.0	13.6
22	32.7	20.2	136.5	156.4	1.5	10.0	11.1
23	35.4	16.4	111.6	133.2	1.6	8.2	10.0
24	35.1	16.6	116.2	138.1	1.6	8.5	10.2
1	30.8	19.8	160.3	181.5	1.6	11.7	12.9
2	32.6	14.1	103.2	124.0	1.5	7.6	9.2
3	32.6	14.0	104.5	125.9	1.6	7.6	9.4
4	32.2	14.4	116.8	138.9	1.6	8.5	10.2
5	30.4	22.0	183.5	205.0	1.6	13.4	14.8
6	29.8	22.1	179.0	199.5	1.5	13.1	14.6
7	31.8	26.3	190.7	211.4	1.5	14.0	15.6
8	30.8	24.2	182.3	203.3	1.5	13.3	14.9
9	30.2	23.9	180.5	201.6	1.5	13.2	14.8
10	29.8	24.6	182.8	203.9	1.5	13.4	15.0

These columns are part of the heat balance portion of the data output. Other columns included temperatures, dewpoint, ventilation rates, and the concentrations and production data for ammonia and carbon dioxide. Dust data were tabulated in a separate file.

10. Appendix C - Energy Balance Equations

1. Psychrometric Equations:

```
    P = (10**(10.79586(1.0-TT)+5.0282ALOG(TT)+
        1.50474E-4(1.0-10**(-8.29692((1.0/TT)-1.0)))
        +0.42873E-3(10**(4.76955(1.0-TT))
        -2.219598)(760)
    W = 0.622 P/(B-P)
    H = T + W(2501+1.86T)
   SV = 2.16(T+273.16)/(B-W(B)/(0.622+W))
   WS = 0.622 PS/(B-PS)
   RH = (100W/WS)/(1.0-((1.0-W/WS)(PS/B)
```

where P = vapor pressure, mm Hg

TT = 273.16°K/(dewpoint°K)

W = humidity ratio, kg moisture/kg dry air

B = barometric pressure, mm Hg

H = enthalpy, kJ/kg dry air

SV = specific volume, m^3/kg dry air

WS = saturation humidity ratio, kg moisture/kg dry air

PS = vapor pressure of saturated air, mm Hg, and

RH = relative humidity, %

2. Ventilation Rate:

$$Q = V A$$

where Q = ventilation rate, m^3/s

V = exhausted air speed, m/s

A = duct area, m^2

3. Conductive Heat Losses:

$$C = E\ (TI-TO)\ N$$

where C = heat loss, kJ/h

E = exposure factor, kJ/(h.°C.bird)

TI = inside temperature, °C

TO = outside temperature, °C

N = number of birds

4. Supplemental Heat Input:

a. Hot water;

$$H = (HWI-HWO)\ F\ A$$

where H = heat input, kJ/h

HWI = inlet water temperature, °C

HWO = outlet water temperature, °C

F = water flow rate, L/h

A = Specific heat capacity of water,

= 4.187 (kJ/(°C.L)

b. Brooder;

$$B = E\ V\ N$$

where B = brooder heat input, kJ/h

E = gas energy content, 34.0 kJ/m^3

(Parkland Gas Co., Stony Plain, Alta.)

V = volume flow rate of gas, m^3/h

N = number of brooders

c. Total;

$$S = H + B \quad .$$

where S = total supplemental heat, kJ/h

5. Ventilated Energy Losses:

$$THL = Q(HI - HO)(3600)/SV$$

$$LHL = Q(WI - WO)(3600)/SV$$

$$SHL = THL - LHL$$

where THL = total heat loss, kJ/h

LHL = latent heat loss, kJ/h

SHL = sensible heat loss, kJ/h

Q = ventilation rate, m^3/s

HI, HO = inside and outside enthalpies, kJ/kg dry air, respectively, and

WI, WO = inside and outside humidity ratios, kg moisture/kg dry air, respectively

SV = specific volume, m^3/kg dry air.

11. Appendix D - Error Analysis

Several instruments and equations were utilized in this study to determine the heat and moisture loads and air quality within the two pullet rearing facilities. However, errors associated with measurements and observations were present in this study. An error analysis was performed, as shown by Mitchell (1983), on these measurements by partial differentiation of the equations used and inserting the absolute error associated with each parameter.

1. Dry-Bulb Temperature Measurement:

    Accuracy of curved-matched thermistors

    UUB 31J1 - 1000 ohms at 25°C,

    = +/- 0.2°C over range of 0-70°C.

    = +/- 0.3°C over range of 0 to -25°C.

2. Dewpoint Measurement:

    Accuracy of hygrometer = +/- 1°C (0-70°)

    = +/- 1.5°C (0 to -25°C)

3. Ventilation rate:

    Duct area = 0.258 +/- 0.0005 m^2

    Most error at low air speeds: 0.88 +/- 0.8 m/s

    Ventilation rate = 0.23 +/- 0.2 m^3/s

4. Total Heat Loss:

    a. Using psychrometric chart, and taking the worst possible instances;

    Enthalpy = +/- 2.0 kJ/kg dry air

    HI - HO = +/- 4.0 kJ/kg dry air

    Specific volume = negligible variation

b. Ventilation rates = +/- 0.2 m^3/s

c. Assume $Q = 0.23\ m^3/s$, $HI - HO = 30$ kJ/kg dry air,

$SV = 0.8\ m^3/kg$ dry air

as these values give the widest error range, particularly at low ventilation rates.

d. THL = 8.63 +/- 6.92 kJ/h (80.0% error)

This error is reduced (to 32%) at normal ventilation rates (0.8 m^3/s).

5. Latent Heat Loss

a. Humidity ratio = +/- 0.0006 kg moisture/kg dry air for a barometric pressure of 705 mm Hg.

$WI - WO$ = +/- 0.0012 kg moisture/kg dry air

b. Assume $WI - WO = 0.013$ kg moisture/kg dry air

c. LHL = 3.74 +/- 2.88 kJ/h (76.9% error); for $Q = 0.8\ m^3/s$, error = 27.4%.

5. Air Quality Measurements:

a. Accuracy of analyzers = +/- 2% of reading

b. Production rates = Concentration x ventilation rate

Assume CO_2 = 2500 ppm, $Q = 0.23\ m^3/s$, NH_3 = 25 ppm, thus error found was

CO_2 = 88.9% (for Q = 0.8, 27%)

NH_3 = 88.9%

12. Appendix E - Bird Target Weights

Bird Mean Target Weights in Grams:

Week:	Hy-Line W-77	Shaver S288
1	55	90
2	110	180
3	170	260
4	240	350
5	310	440
6	390	500
7	470	560
8	550	610
9	640	670
10	740	725
11	850	780
12	950	835
13	1040	890
14	1110	945
15	1110	1005
16	1220	1070
17	1270	1125
18	1320	1180
19	1370	1240
20	1420	1300

13. Appendix F - Cage Bird Heat Production

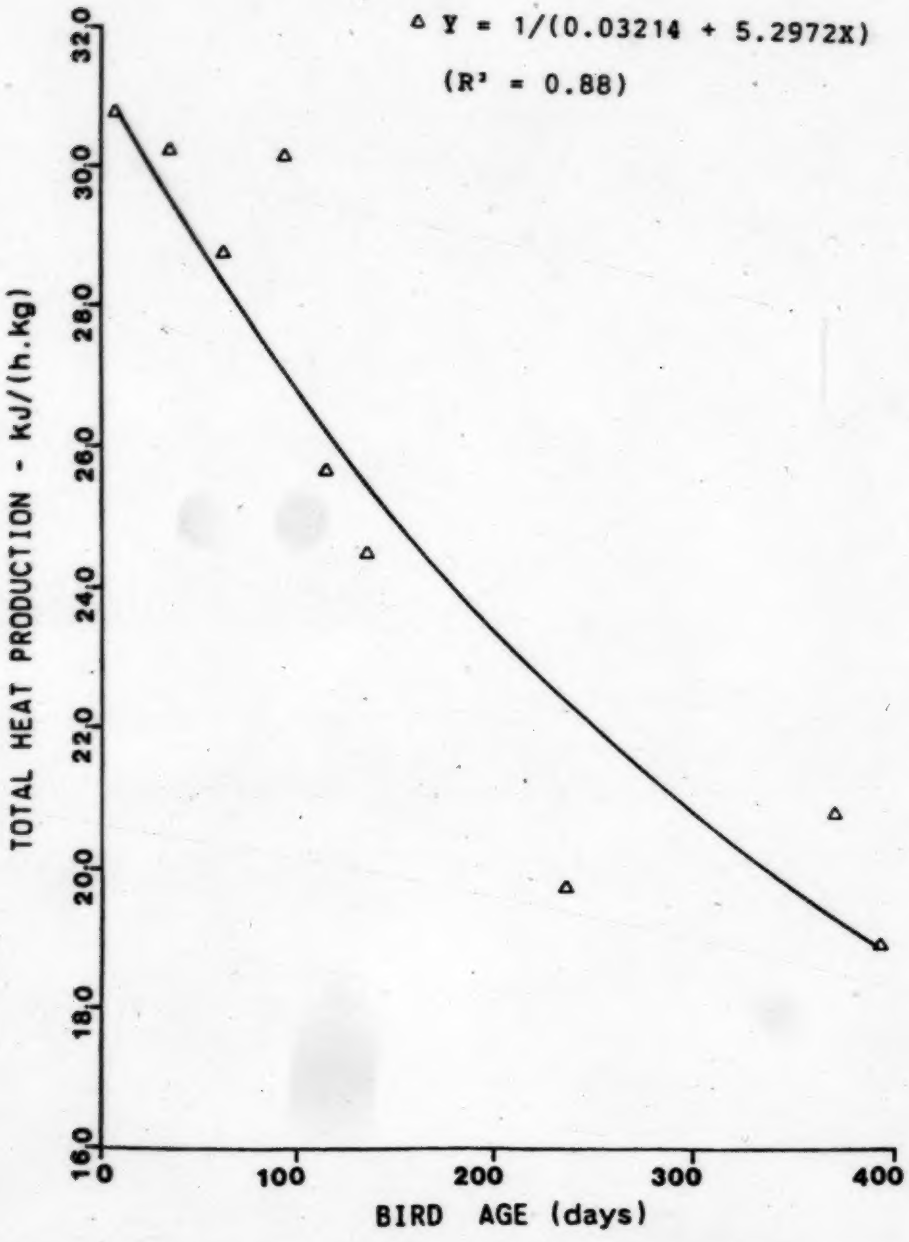


Figure F Total heat production of replacement pullets in Barn B and cage layers.

14. Appendix G - Bird Heat Production Tables

Table G. BIRD TOTAL HEAT PRODUCTION VALUES DURING DAY AND NIGHT FOR BARNS A AND B - MEAN MEASURED VALUES.

Bird age, Days	Bird total heat input Day	Night	Percentage reduction day to night,
	----kJ/(h.bird)---		%
BARN A:			
10	1.8	2.9	-61
36	9.1	4.6	50
61	15.1	13.7	10
90	21.3	18.2	15
BARN B:			
6	3.6	1.2	67
35	15.8	11.3	28
63	23.1	15.9	31
93	33.9	21.6	23
113	32.1	24.0	25
134	32.3	29.0	10

15. Appendix H - Carbon Dioxide Production Tables

Table H. MEAN CARBON DIOXIDE PRODUCTION AND CONCENTRATION DATA AND VENTILATION RATES FOR THE TWO BARNS.

Bird age, days	CO_2 concentration Day	Night	CO_2 production Day	Night
	--- ppm ---		-- mL/(h.bird) --	
BARN A:				
10	2360	1610	312	200
36	1770	2110	756	301
61	2460	1770	700	517
90	3350	2580	908	600
BARN B:				
6	2930	2750	466	235
35	2840	2920	1000	807
63	2200	2110	1513	1037
93	1940	1800	2148	1442
113	1890	1730	2244	1647
134	1730	1620	2358	1870